LAMONT-DOHERTY GEOLOGICAL OBSERVATORY
of Columbia University
Palisades, N. Y. 10964

TECHNICAL REPORT No. 3
CU-3-75

THE INSTRUMENTED NEUTRALLY-BUOYANT FLOAT PROGRAM AT COLUMBIA UNIVERSITY

by
T. E. Pochapsky

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This work was supported by the Office of Naval Research under Contract N00014-67-A-0108-0011, Project No. NR 083-243.

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ABSTRACT

Instrumented neutrally-buoyant floats were used in a series of experiments performed over a number of years starting at the Hudson Laboratories of Columbia University in 1957. This report reviews the scientific motivations for such experiments along with the continued instrument development required. The early work was the first to measure actual oscillatory vertical displacements of tens of meters such as might be associated with internal waves in deep water and also revealed intense vertical shears of the horizontal currents at all depths. Attempts to show that motions satisfied the dispersion relations for internal waves were frustrated by the noisy character of those motions. Such studies were done using clusters of intercommunicating floats hovering near the same depth. Important contributions to the kinetic energy by internal waves were found but the importance of intrinsically turbulent motions remains enigmatic. Inertia currents were shown to dominate almost everywhere. The role of those currents in energy transformations has yet to be established and detailed measurements of their changes with depth may be important in that regard. Measurements of the total current vector in profiles as a function of depth were performed and these showed the presence everywhere of large gradients such as were observed locally at clusters.

Most of the scientific aspects of this work have been reported in previous publications by the author but little has been presented on the type of instrumentation and on the methods of acquiring and processing data. One of the purposes of this review is to present essential details of those experimental aspects.

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INTRODUCTION

Ocean parameters such as temperature, pressure or current which are measured at a point have values that are unsteady and noisy in time. It is expected that measurements in a Lagrangian sense may yield data more closely related to local physical processes than do Eulerian point measurements. In the former case, process is followed as it unfolds in a given volume of water; in the latter, the individual states of a succession of volumes is observed. In the Lagrangian scheme, the local shears are those associated with the relative motions between two particular particles while in the Eulerian they are between a fixed distance which travels in an unsteady fashion relative to the fluid. In the deep ocean where small-scale internal wave and turbulent motions contain a significant kinetic energy at wavelengths of the order of 100 meters and periods of 10^4 sec, horizontal particle velocities, internal wave phase velocities and large scale flows are all of the order of 1 cm sec^{-1} and so large differences are to be expected between the two types of measurements. The Lagrangian should not have the Doppler contamination of the Eulerian. On the other hand, measurements of the absolute displacement and velocity history at a free float which tags a given volume poses more of an experimental challenge than do measurements at anchored installations. For this reason a simple Lagrangian problem of measuring movements between pairs or clusters of particles was taken on initially. In this way, measurements are filtered at the source in that barotropic motions are rejected while shearing motions form the primary input. Later, as techniques were established and a better appreciation of the magnitudes of oceanic flow parameters was obtained, it was possible to expand the

capabilities of the measuring system and so obtain measurements of total motions. This report reviews methods in the instrumented neutrally-buoyant float program as developed by the author to obtain these various measurements. It also sketches the scientific program for which such instrumentation was designed and points out some of the important scientific findings. A more thorough consideration of scientific aspects is presented in individual publications which will be referenced in this report. A review of those findings up until the time that profiling experiments were initiated has been published (Pochapsky, 1971) while a review of current profile measurements is to be published (Pochapsky, 1975).

The previous paragraph can be written now as a confident expression of expectations. Although the experimental philosophy has not changed, such justification could not be made early in the program when the small-scale state of oceanic motion was unknown and when the amazing development of solid-state electronics could not be anticipated.

The development of instrumented neutrally-buoyant floats started under the author's direction at the Hudson Laboratories of Columbia University in 1957 after J. C. Swallow (1955) had already developed the idea of using neutrally buoyant floats and followed their paths at preset depths by tracking pingers attached to them. This was at a time when transistors were a novelty and the launching and recovery of sizable objects at sea were major operations. A philosophy of instrumentation was taken on in the face of these difficulties which led to a number of requirements. Among these are: 1) a float which can be handled easily by one man and so which weighs approximately 50 lb (22 kg) on deck, 2) a float which can be produced in quantity and

lost without experimental or financial catastrophe, 3) a float which transmits data directly to a listening ship so that the acquisition of data does not depend on the ultimate recovery of the float, 4) a data transmission system which uses a minimum of battery energy per data point, 5) acoustic intercommunication between floats, 6) electronic instrumentation which can be altered to investigate novel features of small-scale motions as they are uncovered and which can be changed to take advantage of the accelerating development of solid-state electronics, 7) floats which could be produced eventually at a low enough cost for them to be considered expendable, 8) a measuring system which allows efficient storage of data eventually within a float, which data could be obtained on demand, etc. Such an approach remains appropriate today when the next major stage of development is of disposable floats which are dropped from airplanes or ships in transit and which return to the surface eventually to transmit their stored data to satellites.

Floats were first built of 8-in nominal diameter heavy-walled pipe, 20-in long, sealed by means of standard pipe caps so as to displace 60 lb (27 kg) of water. They were replaced afterwards by spherical containers which have larger payload to total weight ratios. The arrangement on the exterior of a sphere as used in experiments at sea is illustrated in the photograph of Fig. 1 which shows a recovery radio antenna being attached prior to launching. A thermistor housing, hydrophone and pinger are visible just under the sphere and the small cylindrical dropper and attached disposable weights used to allow return to the surface are shown suspended farther below at the end of a thin rod. The end frames expedite handling and recovery.

The engineering of the electronics circuitry used in

Fig. 1. Launching an instrumented float

all phases of data handling was done by William Branscomb and the mechanical design was carried out by Seymour Adler. Success in the various experiments would not have been possible without the creativity and practicality of these men. Both have since gone into other challenges and are not available to contribute directly to this report or to review it. The author has tried to interpret and copy their records faithfully and all misstatements and errors can be attributed only to him.

The field of electronics is developing so rapidly that circuits often become obsolete shortly after they are developed so as to be replaced by simpler and less expensive circuitry. Such obsolescence is expected of much of the circuitry presented here. An exact copying of the circuits by others is not expected and so most circuit parameters have been omitted. The general circuit layouts, however, should serve to point out operational features to be taken into consideration and may help warn of difficulties which appear only at sea. They should also help in decisions as to which newly available components are appropriate replacements. A brief description of the early instrumentation has been published in the ISA Journal (Pochapsky, 1961a) and as a Hudson Laboratory Technical Report (Pochapsky, 1959).

ACOUSTIC METHOD OF DATA ACQUISITION

Transmissions of data by sonic means were used to supply information as it was sensed and to allow inter-communication between floats. The reception of such data during the course of an experiment allows a continuous monitoring at the ship and any inconsistencies in the format of data received helps diagnose experimental short-comings on location. For example, an amplifier gain which is excessive in a float can be surmised when the number of extraneous pulses grows as the sea state increases and this can be corrected in the following drop.

As already noted, individual readings of temperature, pressure, etc. at a float are transmitted in a pulse-time format. For this, a pinged doublet is transmitted in which the time between pings in the pair is controlled by the parameter to be measured. Doublets are sent repeatedly at a clocked rate which is set somewhere in the range of 5 to 15 sec.

Individual pings in the sensed-data doublet are separated by a time which varies from 50 to 550 ms over the full scale of the parameter to be measured. A non-zero lower value is used to avoid interference by echoes off the hull of the ship. The resolution or accuracy with which a particular parameter is measured depends on how closely the tripping time for each pulse can be determined at the ship. In turn, the accuracy of establishing the time of initiation of a ping depends on the rise time of the ping burst which in turn depends on the frequency. The higher the frequency the better the resolution, not to mention the less the weight of the pinger and the higher its efficiency. Unfortunately, sound is attenuated in

propagation at a rate which is proportional to the square of the frequency and frequencies much higher than 10 kHz require unacceptable weights of batteries in order to propagate distances much beyond 10 km. On the other hand, as the frequency is lowered the pinger weights and mechanical Q's (resonant sharpness) increase and the resolution falls. The decision was made to work in the 10.5 to 13.5 kHz frequency range even though an efficient low-Q sound source of light weight and acceptable cost was not available commercially. It was necessary to develop such a transducer at the Hudson Laboratories and the characteristics of this ceramic driven sound source have been described by the author (Pochapsky, 1960).

Pressures and temperatures are determined to a resolution of 1 part in 5000 using two pings or two transmitted bits and leaving the time analysis to be done in the laboratory. If that count were made at the float and transmitted, over a dozen ping bits in sequence would be required and power consumption would go up considerably as would uncertainties caused by the occasional squelching of individual pings during transmission. An extra four bits would have to be added to obtain the resolution desired for separations. Thus, the transmission of data in digital rather than pulse-time form, although potentially more accurate, has its own difficulties.

1. Pingers

An early version of the pinger developed is illustrated in Fig. 2. The dimensional scale is established by scaling to the size of the ceramic cylinder which is 1.5-in (3.8-cm) in length and outer diameter; the pistons are 2.2-in (5.6-cm) in diameter. In present versions the pistons

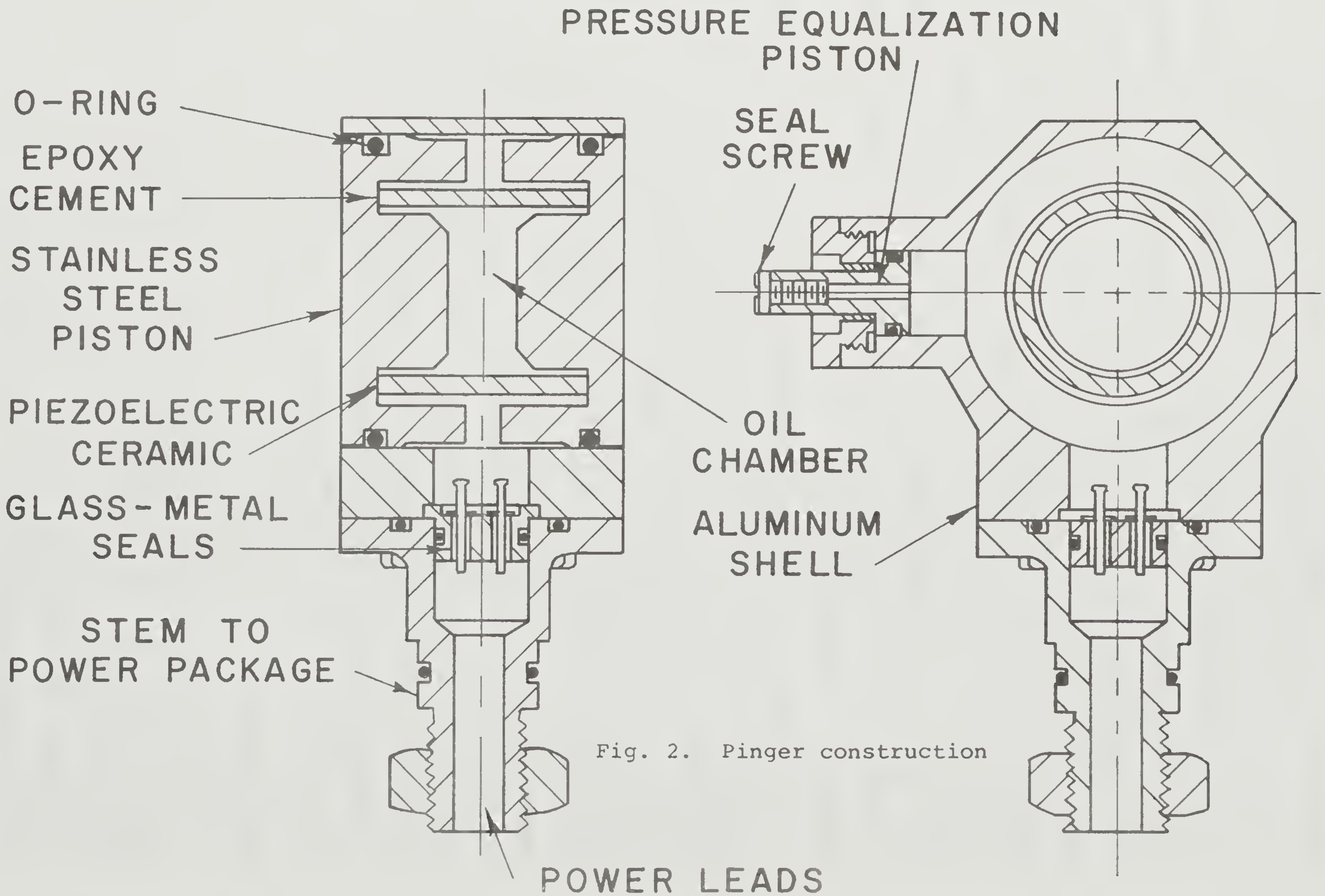


Fig. 2. Pinger construction

are made of Invar metal alloy in order to reduce the possibility of thermal cracking of the ceramic. Also, the outer housing is cast. This design was stabilized for convenience and there is no reason why it should not be simplified. For instance, the piston assembly can be enclosed in a rubber boot so as to avoid the need for O-rings and a pressure equalization piston. A thick loosely fitting aluminum sleeve is still necessary around the pistons in order to reduce the multipole radiation generated by the silicone oil within.

Some typical pinger parameters are noted here: 1) electrical Q = 7.5, 2) equivalent resistance in water = 2000 ohms, 3) efficiency = 55%. The acoustic pressure measured at 1 mile when driven by 200 v was 30 dyne cm^{-2}. Pingers are now driven at 700 v rms. The same pinger can be used efficiently anywhere in the frequency range 10.5 to 13.5 kHz by tuning a loading coil across it.

As driven by a typical float pulsed oscillator and observed nearby, the pulse shape is remarkably pure. The rise on the first half cycle is almost complete although this implies the presence of frequencies well above 10 kHz. Even when such frequencies are forced, however, they attenuate rapidly with distance and detection times at sea must be expected to be uncertain to within a cycle or so, or to the order of 0.1 ms. In experiments where floats were quiescent, say bottomed 3 or 4 miles away, the successive data points came in with remarkable regularity and showed a variation of 0.1 ms. Part of this steadiness may have resulted because both pulse trains, 7 ms long, follow one another closely and have similar shapes at the ship.

2. Acoustic pulse timing.

The electronic procedures used to detect pulse trains and separate them from ship or marine noises will be described later. The important consideration is that each pulse trips a counter when its amplitude reaches a critical value. The actual trip command, however, is delayed until the subsequent shape of the pulse proves itself to resemble in some way that of the sonic form transmitted at the pinger more than it does the forms associated with extraneous signals. When narrow-band amplifiers are used such decision making is not straightforward, especially in the presence of noise spikes of large amplitude.

Once a signal appears, the tail of its incoming energy is used in making the decision of whether the trip be accepted or not. Tripping could be accomplished by signals 1 ms long but signals are made approximately 7 ms long for purposes of aural and instrumental identification. Any noise spike will generate 1 ms long pulses in the amplifier but few will induce a train 7 ms long. Thus, only 1/6 of this signal energy would be required in the absence of noise. Another method of detection, however, offers itself in which the center of time of a wave train is measured rather than the time at the leading edge. Now the longer the train the more surely and accurately it can be located so that not only is more efficient use made of the extra energy for purposes of identification and so for increasing the listening range but the accuracy of establishing the time is increased. Decisions are made on the basis of how accurately the received train matches in detail a duplicate of an uncontaminated signal near the pinger. Such "matched filter" reception was developed for communications to the ship from a float. Instead of using a fixed 10.5 kHz frequency for

pings in this method, an FM sweep of $\pm$ 0.5 kHz is incorporated into the pings. In this way the time resolution is further sharpened. In sea-going operations where the acoustic signals were not weak, both the rise-time detection and the FM matched-filter or correlator reception gave similar time resolution, approximately 0.1 ms. At times when reception was poor, the correlator method could keep all systems recording accurately during situations in which the rise-time detectors were submerged in noise and even the ear could not make out the cricket-like chirps of distant pingers in the background of oceanic noise.

3. Float separations.

It is a simple matter to build circuitry having convenient time scales in terms of which the pressure and temperature can be measured. The distance between floats can also be expressed in terms of time if the round-trip or transponded time of transit of a ping between floats is used as a measure of distance. The scale of this time, however, cannot be transformed without involving undesirable extra circuits while some minor complications occur when the transponded time is used directly. For example, when floats of a pair are near one another the travel time is small or less than the 550 ms full-scale time of separation of sensor-data pulses. There then can be confusion in distinguishing between separation and sensed data. For this reason, only one float called a master, or M, float is given the role of interrogator and the other listening or slave, S, floats give responses which are delayed by 750 ms. Furthermore, slave floats can be interrogated only once in the repetition cycle of the interrogating float and so they do not respond to the second ping of the master's data

doublet or to surface or bottom reflections of interrogating pings. A slave float is internally clocked to a 20-sec repetition rate but the clock is disabled when the slave is interrogated periodically at a faster rate. The internal clock is active only when the S float is by itself or is unexcited, in order to generate signals for passive acoustic tracking. To distinguish between themselves the single M float in a cluster transmits at a frequency of 10.5 kHz and listens at 13.5 kHz while the associated S floats all transmit at 13.5 kHz and listen at 10.5 kHz.

The overall method of sonic operation is illustrated in Fig. 3. Here, two spikes represent the M ping doublets heading toward the ship and a slave float. The S float responds with its own data doublet at its own frequency. This response is heard by the M float which repeats it immediately at its own frequency. The two different pulse pairs sent by the M float are separated in time by the S float transponding or echo time and all are heard at the ship at a frequency of 10.5 kHz. For this cycle the ship instrumentation prints out the temperature or pressure at both floats along with the radial separation.

When only one or two S floats are used there is no confusion as to the identity of the slave responding. A number of procedures have been investigated to permit the use of a greater number in a cluster. These included: 1) interrogation of the different S float by the M float at different frequencies, 2) interrogation at the same frequency but using coded interrogating pulses, and 3) clocking the listening time of the S floats so that only one is active at one time. This listing is in the order with which the different systems were tried but it also starts with the one most difficult to achieve.

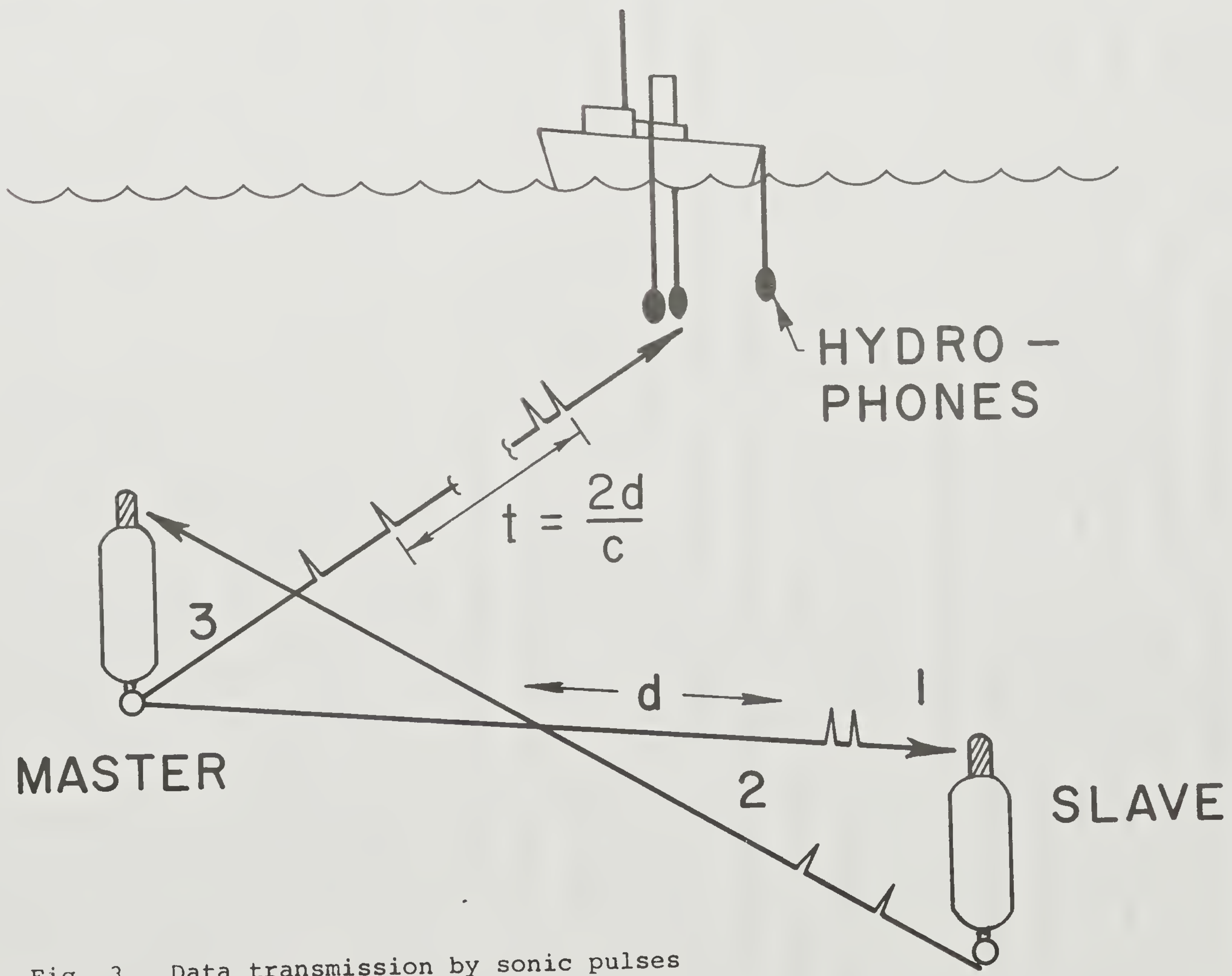


Fig. 3. Data transmission by sonic pulses

The first method as tried involved four S floats interrogated in sequence by an M float at the frequencies of 8, 9, 11 and 12 kHz. The S floats all responded at 10 kHz while M transmitted data at 13 kHz. The M internal cycling was such that pings were sent every 12 sec and the series of 4 frequencies was repeated every 4 min. This cycling system allowed two M floats to be used in the same S cluster. In this way the two dimensional positions of S floats relative to the M floats rather than merely a radial separation from one could be obtained. If desired, the absolute movements of the S floats also should be obtainable by letting them move relative to two bottom-anchored M floats. Operation of this system failed at sea even though all components functioned prior to sailing. Some direct telemetry occurred, however, so that the experiment was not a total loss. A number of factors contributed to the failure and the most important was an overevaluation of the capabilities of listening amplifiers, pingers, etc., as based on the good fortunes of previous operations. Premature recalls by sea noises associated with squalls and by screw noises at critical times added unexpected new difficulties. Correction of such problems was hampered by the limitations imposed by small battery energy, weight, and limited space within a shell. Improvements since then (1963) should allow successful operation of such a system today.

At this time, the sure acquisition of data was the prime motivation and because an early functioning of the previous system did not seem likely a return was made to the simpler two-frequency system. Selective interrogation was now attempted by using coded pulses. The coding scheme involved an M float which generates a triplet rather than a doublet pulse. The additional pulse appears just after the first at a time determined by the coded time appropriate

to the S float to be interrogated. For example, when four S floats are used they may be made individually active by being being interrogated with differing coded pairs in which the separations are 10, 20, 30 and 40 ms. Successively clocked M pulses generate doublets in sequences of these coded times while a third pulse still yields sensor data. Only one S float is interrogated at a time between two successively clocked M pings which are approximately 8 sec apart. After the 40-ms coded doublet is sent, the next clocked pulse reinitiates the sequence with the 10-ms coding. In this fashion four S floats can be interrogated repeatedly in sequence without interfering with the sensor data doublet which has a time delay from the clocking pulse greater than 50 ms.

In the third system above which uses a clock, it is necessary to use separate clocks in each S float and each of these must have an accuracy measured in seconds over a duration of a week. Otherwise, different S floats would be activated at the same time. Electronic clocks have this accuracy. Available mechanical clocks with jewelled movements have relative time shifts which are at least a fraction of a minute per day. The "on" times of the different S floats must be phased relative to one another at the time the cluster is dropped.

Both the code and electronic clock schemes were developed and both passed laboratory tests. They too failed at sea for small but fatal reasons. They are mentioned here to note that such methods are promising but that they have to pass a "baptism of fire" at sea. The coding procedure failed because it was temperature sensitive and excitation of the S floats did not occur in waters below the thermocline. The electronic clock system failed at the time

pingers were attached to the exterior of a completely sealed float in which the clock was shielded by a 1/2-in thick wall of aluminum. The transient current in the shell during a ping at the time of attachment reset the clock and so threw it out of synchronization. The occurrence of this reinitiation was erratic and it took place in a frustrating manner. Mechanical clocks are not a desirable alternative but they were brought along for the unlikely event that they might be needed,— they were and they enabled obtaining the basic data sought.

When S floats are used only as transponders for determining separations and not to transmit sensor data, it is convenient if they transmit identifying coded doublets. Then many of the procedural problems noted above involving selective interrogation together with sensor measurements vanish. When the number of S floats is small, all can be interrogated by the same M doublet and have their differing coded replies repeated by the M float. The various codes then can be used directly to determine the different S-float distances. When two coded doublets overlap, they can be untangled by means of logic circuits. This method was used to measure the absolute motion of an M float relative to anchored S floats under conditions in which transponding S floats were anchored three miles down while the M float traversed any depth at horizontal distances of up to at least 3 miles from the transponders. The weight of the M float can be set so that that float hovers at a desired depth or so that it ascends or descends the entire ocean column while it maintains acoustic contact. In the latter case, vertical profiles of the various parameters are obtained.

Both S and M floats can be heard at the ship and

interrogated from there. The prime source of data, however, is the M float and it is this which feeds the listening and processing equipment. Because floats move slowly and the ship's engines are noisy, listening is done with the ship laying to and the main engines off. Signals are received at three spaced hydrophones which trip a 3-beam memory oscilloscope. The three relative times of arrival of a pulse establish the bearing of a float relative to the ship. A circular slide rule has been devised to simplify converting relative times to bearings. A pinger over the side is used to establish range. Simple over-the-side hydrophones are used and their conducting cables shift away from the vertical as the ship drifts. Consequently the geometry of the hydrophone array is not fixed and the float bearing is uncertain, usually to $\pm 10^{\circ}$. Attempts to improve accuracy by hardening the array and using a computer face more difficulties on typical vessels than are immediately anticipated.

The most important reason for locating a float relative to the ship often has proved to be to establish the position of the ship rather than that of the float. For example, in equatorial work done at a time before satellite navigation was available it was necessary to rely on star fixes and dead reckoning procedures in order to establish the position of the ship at any time. Considerable skill at this was acquired along with an unexpected faith in dead reckoning but an inordinate amount of effort was required for mediocre and uncertain results and every squall added its measure of difficulties. If the position of the ship were known at all times, say to a relative accuracy of a fraction of a kilometer, then acoustic ranging alone relative to the drifting ship would be adequate for determining the course required to return to the proximity of the float being monitored. When the actual position of a float is of major

importance, then its course can be determined accurately relative to bottom anchored transponders which are repositioned occasionally so as to keep within acoustic transponding distance of the freely wandering float. Transponders have been set to respond to the ship's fathometer and ranges to it are traced on the fathometer chart. For convenience, transponders sometimes have been made to reply at a frequency which differs from the interrogating frequency and those replies alone, uncluttered by bottom reflections, appear on the chart.

In most of the work at sea, data-pulse times were measured on board ship so as to monitor changes in physical parameters as they occurred. This involved much electronic equipment and eventually 5 relay racks of apparatus, which included auxiliary backup and test equipment, together with associated technicians were taken along. Later, however, the number of essential racks was reduced to two and the assurance previously provided by the extra racks which printed out data on location was now obtained from tape recordings of the acoustic signals in analogue fashion and in real time for subsequent analysis on land. Data obtained in land-based laboratories from such tapes have a remarkable repeatability and generally are of higher quality than is obtained at sea, particularly during times of experimental difficulties. Furthermore, as navigational aids have improved and the electronics associated with those aids become a part of standard shipboard equipment, the equipments and number of technicians required for float work becomes substantially reduced without reducing the flexibility of experimental procedures.

PROCEDURE IN AN EXPERIMENT

A float shell is a free vehicle for carrying instrumentation needed to obtain data. A float registers temperatures, pressures and distances during its descent or ascent or while it hovers at a particular depth or on the sea floor. Once it leaves the ship, nothing can be done to change the condition or settings of the instrumentation. If it stops emitting sound or if the weight dropping release becomes defective it most likely will never be recovered. Preparation before launching consequently has to be done thoroughly so that the vehicle will descend at a calculable speed to reach and hover at a specific depth for the time desired and meanwhile carry instrumentation which goes through specific data sequences. Procedures are not identical in all experiments but they have much in common and typical procedures will be sketched here.

A routine involves preparing electronic and mechanical instrumentation in a group of floats, trimming the floats to hover at a desired depth, launching, maintaining acoustic communication and recovering floats as they surface. It is usual for floats to arrive at experimental locations with acquired defects. Transistors and printed circuit boards may be loose in their sockets as a result of the vibrations of transit, calibrations can change, etc. Batteries are not put in floats prior to shipment because of the possibility that they may be overheated by exposure to the sun during shipment. Consequently, floats are opened and given final adjustments just before they are to be used.

The average density of a sealed float is set just prior to launching so that it will be neutrally buoyant at a selected depth. This is done in a slender tank made up of two

55-gal drums in line which is filled with sea water. Lead sinkers and strips are attached to the float until it tends to hover near the center of that tank. Such a balance is sensitive to a weight equivalent to approximately 5 gm. Care must be taken that there is no vertical temperature or salinity gradient down the long tank and that no air is trapped in the various fittings on the exterior of the float. Additional lead weights are then added to change the average density of the float assembly from that of the water in the tank to a value which makes the mean density of the float at depth equal to that of the water in situ at that depth.

Not only the temperature and salinity must be considered when adjusting the density of a float but effects of pressure must also be anticipated. The latter depend on the average compressibility of the float shell together with its external accessories. Mean float compressibilities have values which vary in the range 1/3 to 1/2 that of water depending on the shell shape and wall thickness as well as on the characteristics of accessory buoyancy elements. The temperature-salinity correction is highest in the trim for hovering in the main thermocline where it changes approximately 50 gm in going from $25^{\circ}C$ surface waters down to $10^{\circ}C$ waters. The pressure correction at all depths is approximately 70 gm per km of depth.

Launching is usually done off a slip line at the stern. Just prior to launching, the whip antenna, 1.5 m long, is installed with an attached 40 cm square pennant of orange nylon. Simple tests establish that the listening hydrophone, pinger, recall clock and recovery radio are functioning properly at this time. Release is done by one man who uses the line to ease the float into the water when the

stern and sea are favorably positioned.

Once free of the ship, a float must remain in acoustic contact with it. The use of frequencies near 10 kHz means that a float is apt to be out of listening range and temporarily lost when the ship drifts approximately 5 miles from it. Communication worsens in heavy weather in which winds push hard to separate ship and floats. Time gaps in communication caused by a loss of acoustic contact result in corresponding losses of data. Consequently, once a cluster is launched, effort must be continued in a shipboard laboratory which has facilities for tracking floats, printing partially processed data and exhibiting data sequences which monitor operation of the system. Float-tracking data is used along with information from the ship's bridge to establish positions. In almost all past work technology and operating areas were such that absolute fixes were provided only by the stars and it surprising how many cloudy mornings and evenings there can be during an operation.

Floats broadcast their ascent to the surface by transmitting a continuous sequence of decreasing pressure readings. When a float is a mile or so away horizontally from the ship, acoustic communication may be lost shortly before surfacing as a result of variations in the sonic index of refraction usually present in near-surface waters. The actual surfacing is strongly announced by the radio transmitter. An occasional radio watch is carried out to make sure that silent floats do not surface out of schedule. Surfacing from great depths takes of the order of an hour and so there is adequate time to steam into the surfacing area to be near the float for acoustic and visual location when it arrives at the surface.

Radio location would be simple if a properly installed

direction finder were available. Usually a permanent installation on a ship for the frequencies used, 2240 and 2792 kHz, is not available and improvised installations have to be corrected for the reflection pattern off the ship, including that off rigging altered for a particular operation. A small portable direction-finding radio was used in most instances.

At distances of less than a mile, depending on the sea, the best means of location is by eye. The release of dye on surfacing and the use of a flashing light for night recoveries were both tried. Devices for these functions had to be of light weight and known compressibility. No advantage was found in the use of dyes. Blinking lights were almost essential for recoveries in the dark but experiments were scheduled for day-time surfacing and so the addition of blinkers to the float exterior generally contributed more of a nuisance than benefit. Floats do not have a spar-like shape and lights must necessarily lie close to the water surface where they tend to be hidden from observation even in relatively quiet seas.

Once the vessel pulls up alongside a surfaced float it is a simple matter to pluck that float out of the water with a long boat hook. Depending on the watch on the bridge, the wind, sea, size of vessel, auxiliary propulsion, etc., the operation of coming up to a retrieving position can range from a simple to a time consuming one.

MECHANICAL FEATURES

1. Float housing.

Spherical housings are made of 7075 aluminum alloy. For this purpose, round flat plates were pressed through a

die and these came out as elongated hemispheres, each with a greater wall thickness at the equator than at the pole and with extra wall extended from the equator. The latter excess is machined away so as to leave an equatorial flat on one set of hemispheres and a flat with an O-ring groove on a second mating set of hemispheres. The interior surface as extruded closely approximates a sphere 12-in (30.5-cm) in diameter and is not machined. The exterior is machined into a sphere concentric with the interior everywhere except in a 1/2-in wide belt around the equator. That belt of unmachined thicker wall forms a 1/8-in thick lip on each of a mating pair and sharp clamps are used to bite into those lips so as to join the two hemispheres into a sphere. Complete contact is obtained in the water where the float is exposed to a large hydrostatic pressure. The clamping arrangement is illustrated in the photograph of Fig. 1. A view of the lip and equatorial O-ring groove is shown in Fig. 4 which also illustrates an early version of the electronic board arrangement.

Mecca fittings are used to make electrical connection through the walls.

Two wall thicknesses are used, 1/2 in and 3/8 in, and such floats are good for service up to pressures of 10,000 psi and 7500 psi, respectively. The thickness of the wall on a given float is uniform to approximately 0.01 in. The buoyancy of a 1/2-in walled sphere alone is 20 lb (9 kg); the thinner walled spheres provide 4 lb more.

For disposable floats, machining operations are minimized. A cut is made along the equator but no machining of the wall is done. There are openings only at each pole and these are sufficient to allow for clamping hemispheres together, obtaining an attachment for anchoring, and allowing an external pinger which also serves as a hydrophone.

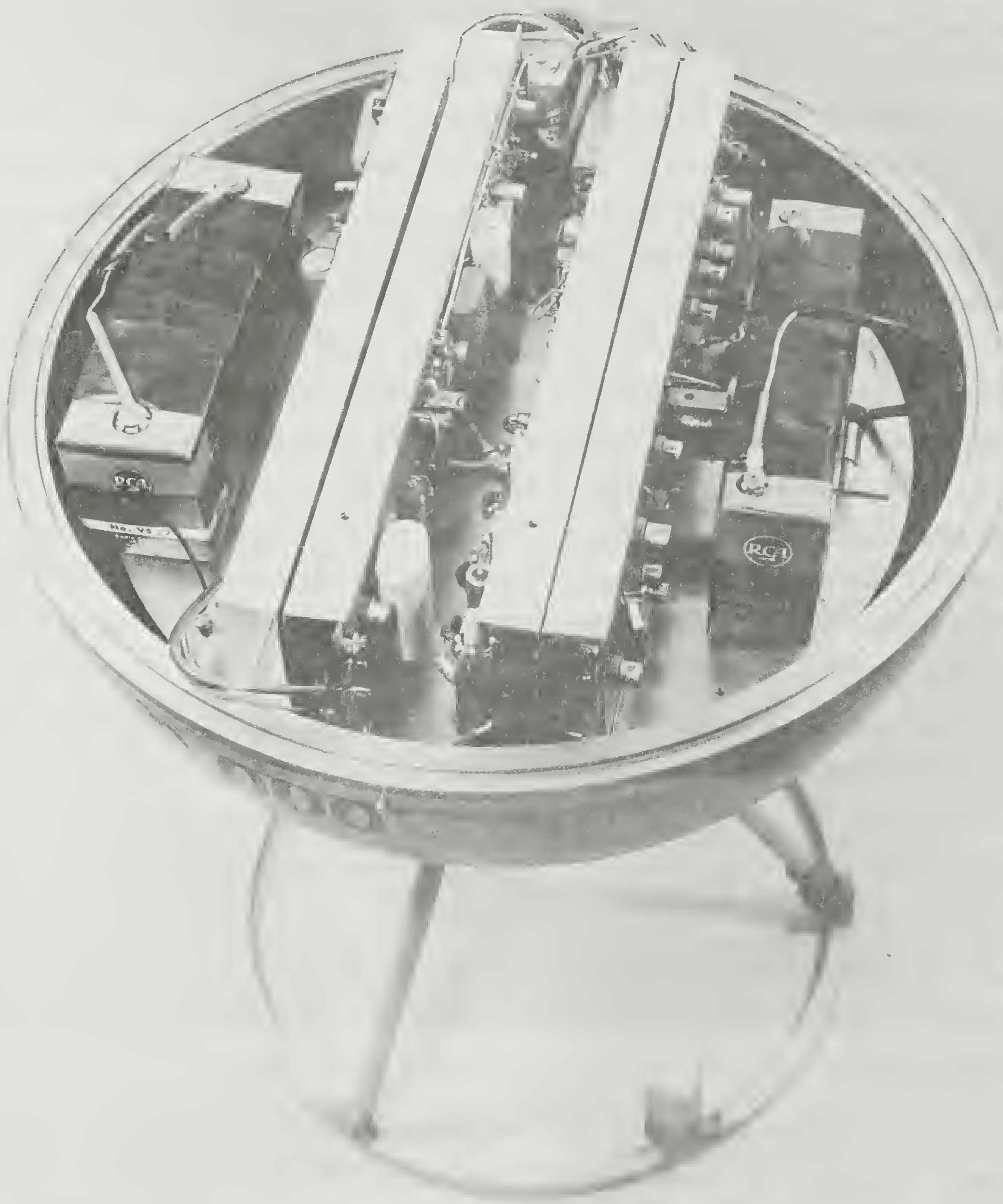


Fig. 4. View of circuit boards in early float

The polar wall thickness is 0.40 in (1 cm). The resulting spheres did not leak or implode at a tank pressure of 10,000 psi but metal started to splinter along the O-ring ridges at pressures above 7,500 psi and plastic flow indentation of the flat amounted to 0.01 in as the pressure was raised gradually to 10,000 psi. Splintering continued as the pressure increased and produced pinging sounds which would be expected to excite transponding circuitry built into the sphere. A number of such transponders were used for several weeks without difficulty at sea at 8,000 psi (567 kg cm^{-2}) pressure.

In order to achieve long submersions, extra batteries and so more pay load than is available may be needed. Extra buoyancy elements must be attached to the sphere and these tend to be brittle, bulky or expensive and can be placed only in the upper section of a float where they are vulnerable to fracture during recovery. Ceramic alumina spheres, 6-in and 8-in diameter and 1/8-in wall (Coors Porcelain Co.), were found to be satisfactory for our purposes and can be nestled into the upper recovery frame. They are shielded from hard raps by means of rubber pads.

A factor in neutrally-buoyant float work is that the compressibility of a float assembly differs from that of the water and so the float and water cannot move together in identical fashion in response to *in situ* pressure gradients. An interesting method of trying to correct this is to attach a large volume of water in a thin-walled bag to the float. Such a bag used in our work was of cylindrical shape for which two hoops, made of 1/4-in diameter aluminum rods bent into 2-ft diameter circles, retained the upper and lower surfaces of plastic sheet, 0.0035-in thick. The cylindrical side wall surface, also of plastic sheet, stretched between the hoops, being secured at the top by the upper ring and

held down a distance of 2.5 ft by the weight of the lower ring. The plastic surface was free of leaks and the cylinder was evacuated on deck so that the two hoops and the plastic sheet collapsed into a thin layer in which no air was occluded. This plate was secured below a float and both sank together at a moderate speed. At an appropriate depth, several small light bulbs imploded so as to produce openings into the bag and water entered slowly. The weight of the lower ring was sufficient to pump water in until the bar, in a matter of several hours, achieved a cylindrical shape which was filled with water having a salinity and temperature close to that present at the equilibrium depth. The volume of water in the bag was 11 times that of the sphere. Further experiments in this direction, perhaps involving larger volumes of trapped water, seem warranted now that the feasibility of such a method has been established.

2. Weight releases.

A float starts its return to the surface at a time preset on a recall clock. That clock starts a motor which has a shaft that protrudes through the case and rotates a finger which secures a small weighted plate. That surfacing weight is released when the slowly rotating shaft twists the finger from a hold position. A typical weight, 2.2 lb or 1 kg, combines the "surface buoyancy weight" and the "density trim weight".

A timing weight dropper is illustrated in Fig. 5. Without attached weights it weighs 4.4 lb (2 kg) in air and 2.2 lb in water.

Some difficulties associated with the use of the recall device should be noted. The electric timing clock was

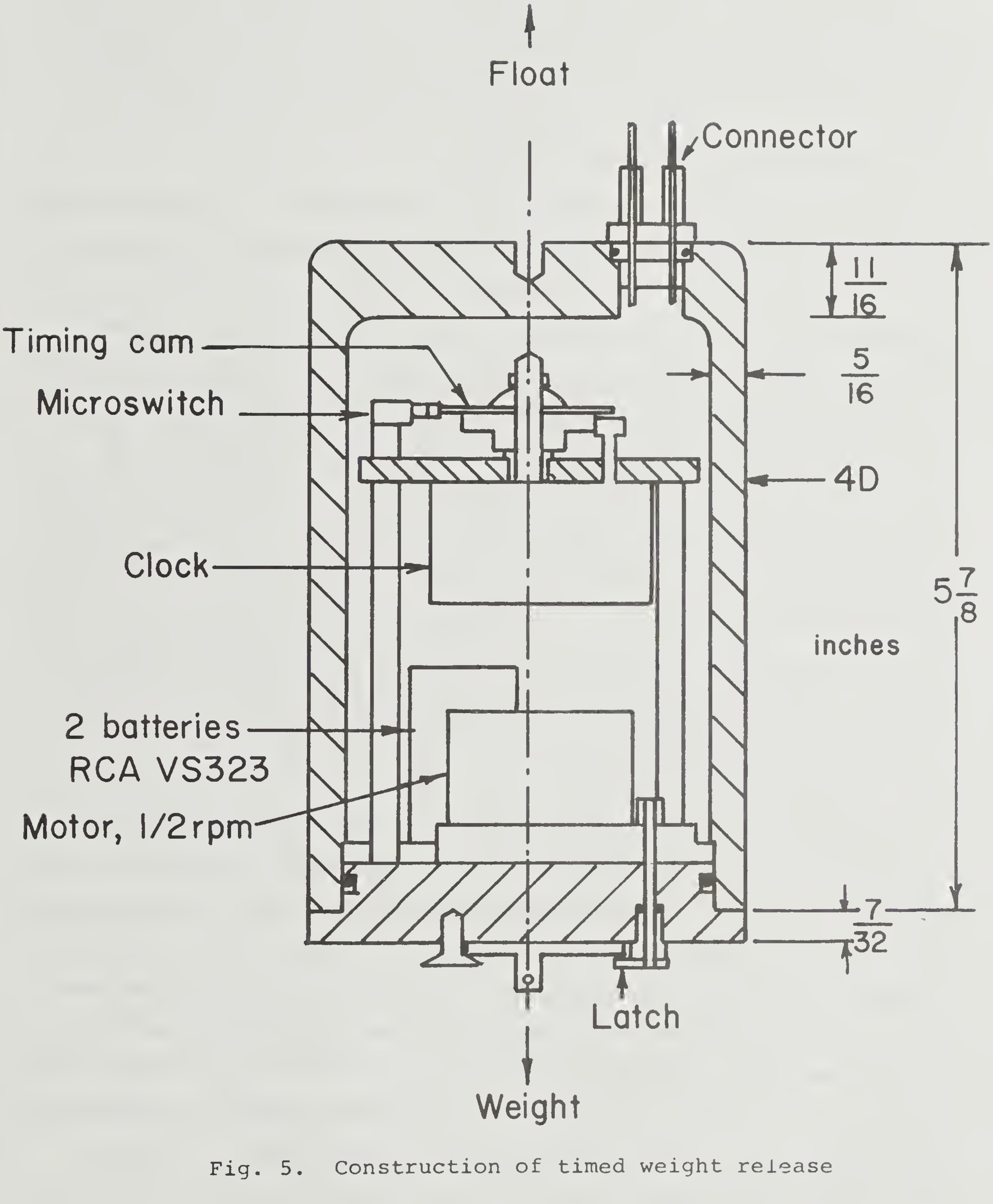


Fig. 5. Construction of timed weight release

chosen on the basis of its high torque and low cost. It has three important faults: Sometimes it 1) stops during launching operations, 2) runs at double time and 3) decides to start making loud ticking noises. All three of these can be diagnosed at the time of launching but double-timing and loud talking may start after launching. As a result, there will be a premature release or the float may ping every clock tick to the surface.

The release motor can be switched on at external leads. When these are connected to the main float shell they can be shorted at appropriate times by recall circuitry. Such circuits offer a means of returning the float on demand merely by transmitting a coded sonic signal from the ship. It affords not only a fail-safe feature but it allows the early return of floats which are not functioning up to expectations. At times, however, rain, shipscrew or other noises found the code and returned floats to the surface, particularly when they were functioning beyond expectations. Recall malfunctions were distressing because valuable data and effort was lost when tracking down an isolated surfaced float. Furthermore, when a key navigational transponder surfaced, the ability to keep accurate track of the ship and other floats was lost.

Dependability of the recall system improved as the coding and ship interrogator were made more complex. The added cost, weight and effort were not welcome and a counter notion grew that it would be better to go in the direction of less expensive floats which could be abandoned rather than more expensive ones that demanded even more effort toward recovery. When a gale brews, there is little inclination to initiate a probably fruitless search and recovery operation for an expensive piece of equipment. Efforts would go better into improving the dependability of basic

circuits and of the preset releases which had been used successfully already. For transponders, this notion of disposability is immediately appealing. No exterior framework, radio or weight dropper is required and a single transducer can function as pinger and hydrophone. Furthermore, float housings can be made to reduced specifications and, for example, severe plastic flow can be tolerated at pressures which would destroy the further usefulness of such floats if recovered. This course was followed and the transponder circuitry developed will be described in a subsequent section.

A second type of weight release was required for profile measurements in which a float sinks slowly to the sea floor, releases its weight and then immediately starts its return to the surface. The requirement was kept that a float should have a surfaced buoyancy near 2 lb while approximately that amount of excess weight over neutral buoyancy was needed for slow descents. Descent velocities near the floor can be very small at times and if the floor is muddy the rate of change of momentum of descent on contact may be so small that not enough force is available to trip a 4 lb weight loose. For this reason, a sensitive mechanical trip was developed that converted a long motion of a leading probe into a short but more forceful motion of two fingers which held the weight against gravity. The construction of this probed weight dropper is illustrated in Fig. 6. It has a feature of a mousetrap,--a sensitive latch which releases an appreciable amount of energy and it is suspected that at least once a fish played the part of a mouse and ended up with a rap on the head as the float started its return upward.

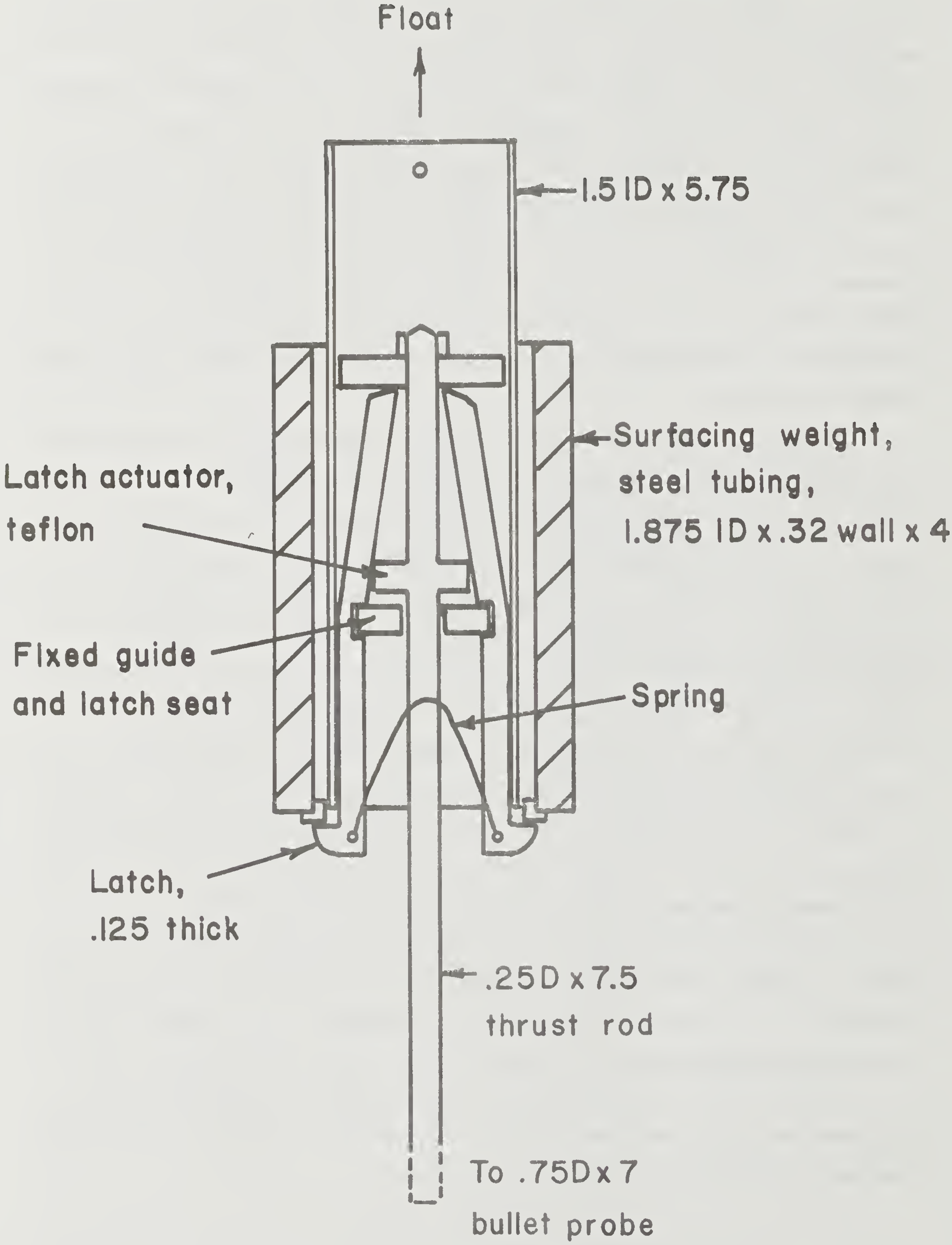


Fig. 6. Construction of tripped weight release

RADIO TRANSMITTERS

Small radio transmitters are useful adjuncts in float experiments. The use of these for the location of floats has been mentioned. In addition they can be used to establish navigational references and to act as acoustic listening stations.

A circuit diagram of the transmitter used in a float for recovery location is shown in Fig. 7. Physical features of the whip antenna are illustrated in Fig. 1. The circuit includes a simple temperature controlled switch which shuts off the current in cool deeper waters. Even when the circuit is not disconnected from the battery, the antenna is so badly detuned when submerged in the conducting salt water that little current is consumed and the battery will last a day or so. The radio-frequency signal is sent in bursts on a 10% duty cycle at a rate of 300 Hz. The average power output is 100 mw. The intensity of the signal received varies as the float bobs in a sea and the resulting sound is quite distinctive and similar to that of an angry mosquito. Range varies with sea conditions and the upper limit, 15 miles, is obtained on a smooth sea. A range of 5 to 10 miles is more typical. Frequencies are crystal controlled and set at 2792 kHz for M floats and 2290 kHz for S floats and transponders.

The practicality of an RF transmitter as a navigation reference in shallow water is evident because bottom anchoring of a radio buoy can be accomplished easily there. Even under what may seem to be favorable circumstances, however, the fixity of such a reference must be established. For example, when a radio buoy was planted on a seamount near Aves Island in the Caribbean, it was found to drift because

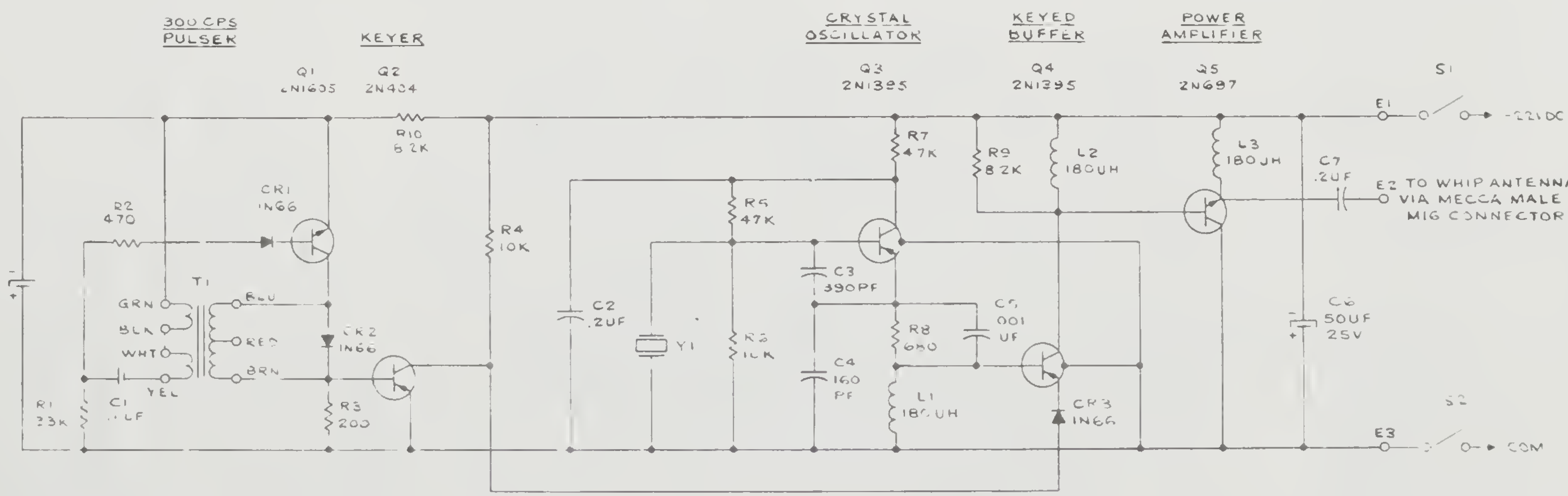


Fig. 7. Float transmitter circuit

the bottom anchor could not bite into the smooth ice-like surface of the seamount. In typical deep ocean, radio buoy anchoring is much more expensive and difficult. Furthermore, it is not sure that a buoy on a line of large scope offers the reference desired, particularly when floats drift out of the buoy area. An alternative may be to accept the drift of a free buoy which is restrained by means of a deep drogue.

Radio buoys have an appeal not only as a temporary reference which makes it easier to obtain bearings after a squall but also as a means of transmitting acoustic data when the ship is steamed in the operating area or otherwise subjected to noise. Typically, disposability was sought. One reason is that any given buoy probably has a time limited usefulness. If, for example, the relative motion between a buoy and float is only 0.1 knot (5 cm sec^{-1}) the two separate by 2 1/2 miles per day and so will be out of acoustic contact in a few days. Recovery and re-launch of a radio buoy is not often convenient. In a simple extreme, styrofoam blocks were used for flotation and these were restrained by drogues suspended on piano wire. Tests with these were conducted on a non-interference basis along with float experiments but both experiments diverged in location and so attention to the radio buoys was minimal. Subsequent analyses showed that wild chases could have resulted because 1) buoys ran freely along the surface when the piano wire weakened so as to break in the corrosive near-surface water, 2) listening gains were set without prior experience, 3) hydrophones were cut off and 4) entire buoys disappeared. The largest culprits turned out to be sharks. Hydrophone cables had teething marks and were sometimes severed by knife-like cuts. Moreover, sharks caught by the crew had stomachs containing styrofoam. The principal lesson of those experiments is that the concepts work within limits

which depend strongly on the experimental location but that it is important to incorporate devices in a buoy which would warn when it is free of its mooring and so misleading.

Experiments with such buoys were not continued because they did not fit into the continuing research program. Nevertheless, more substantial buoys were made up for the event of need. These obtained flotation by filling a small garbage can with plastic foam; a nominal 2-in iron pipe along the axis offered anchorage.

REVIEW OF EXPERIMENTAL OPERATIONS

This review is presented after a general description of experimental procedures so that the meaning of individual operations may be clearer. The development of instrumentation in the float program proceeded in a direction determined by the kind of data sought. Each experiment was a quest for new insights into the smaller scale physical processes in the oceans and new forms of instrumentation were needed although the trials of novelty were not welcome. The first experiments were based on the assumption that only trivial horizontal motions were present at a length scale of a kilometer or less and that these were attributable mainly to turbulent mixing motions. Variations of the pressure gradients in the vertical direction in stratified water were thought likely to dominate over changes in the horizontal direction. For this reason, the first instruments were designed to measure vertical pressure gradients in experiments lasting of the order of a day. At that time (1958) a mechanical method was developed for periods in the range of a fraction of a second to a few hours and used at a sensitivity of 1 dyne $cm^{-2}m^{-1}$ to reveal possible fluctuations of the vertical velocity having values of the order

of 1 cm sec^{-1} over a 1 m depth change. The results showed that only surface waves produced gradients of this magnitude (Pochapsky, 1961b).

A second direction in the study of turbulence is to measure the horizontal dispersion of floats set at a specific depth. It is, however, difficult to place neutrally-buoyant floats at precisely the same depth and differences can amount to from 10 to 100 m depending on the vertical stability of the water. When a pair of floats was placed at the same nominal depth, the horizontal distance between them was found to increase much more dramatically than expected. This behavior was observed in experiments performed at various nominal pair depths increasing in steps of 100 m down to 400 m below the surface. Instead of remaining near one another over a period of an hour, floats of a pair separated with a speed comparable to that of the mean flow at that depth (Pochapsky, 1961b). Moreover, the floats bobbed up and down at amplitudes of a meter of so and at periods somewhat less than an hour in tests which lasted only a few hours.

These preliminary experiments showed the value of continuing investigations in the direction of horizontal dispersion and vertical displacement and the purely mechanical instrumentation was abandoned in favor of electronically augmented means of investigating more accurately and for longer times the manner of vertical movement of a particular float as well as the horizontal separation between floats in a pair. Measurements through 1961 in the eastern Caribbean and at two locations 250 and 400 miles east of Bermuda confirmed that unexpectedly intense small-scale motions, including large horizontal shears, were present and that a possibly tidal throbbing motion took

place in the separation as a function of time. Movements of the water were deduced by means of an analysis of the dynamics required to produce the float motions observed (Pochapsky, 1962b and 1963).

By this time, confidence was gained in the float-pair procedures,—not only in the ability to obtain depth and separation data by following floats but also to send floats free of the ship to desired depths and to recover them a day later. Important questions remained to be answered, such as 1) what role is played by the tides as contrasted to inertia currents? 2) can internal wave dispersion relations be found in the relative motions observed in a cluster of floats? 3) how will a cluster of more than two floats behave? 4) what temperature changes take place at a float? 5) will the implications of the results change if measurements are made over longer periods of time? 6) are the shears sufficient to produce Richardson instability? 7) what magnitudes of motions are present at great depths in parts of the oceans isolated from continental boundaries? In order to answer questions such as these it was necessary to send down more floats at a time, to have them intercommunicate and to have more powerful pingers on floats capable of carrying battery energy sufficient to last a time of the order of a week. In addition, temperature as well as pressure measurements of higher resolution were needed.

Ship time was available in equatorial regions (1962-1963) and it was thought that these areas would have relatively quiet waters in which tidal and inertial motions would be distinctly separate and in which there would be a less confused jumble of activity than found at higher latitudes. Operations there did show a small-scale activity similar to that obtained to the north but differed in the

presence of larger vertical shears of current and the absence of pronounced tidal motions; otherwise, no important extension of knowledge was gained. These areas turned out to be less a source of data than a proving ground for such innovations as were involved in multiple-float data multiplexing for long times. Perhaps the most important result was the feeling that we could do it right the next time. Although a serene experimental environment was expected, the water was very busy as were the squalls and sharks. A report was published to describe the changes of current flow with depth (Pochapsky, 1962a).

The next set of experiments was performed as a two-ship operation (June 1964) just outside the Northeast Channel of the Gulf of Maine. A conservative float-pair approach was taken but now some floats were built to telemeter temperatures as well as pressures. In addition, Savonius rotor current measurements were made on the nearby Shelf. Intense tidal and inertial motions in this region just off the Shelf were clearly demonstrated and the float separations included a strong inertia-period term. It was anticipated that internal waves of tidal and higher frequencies would be unusually intense along the Continental Slope. So far, the data obtained has been analysed and published only in part and results appear only as addenda to other reports.

Cluster experiments were performed again off Bermuda (Nov. 1964) and these definitely established that floats move relative to one another in inertial circles rather than with tidal motions (Pochapsky, 1966). Although a cluster of five floats was used in a drop to the 2300 m level to hover for 5 days, all floats did not maintain communication with the M float. Two did and the three corresponding sets

of pressure and temperature variations found as a function of time are illustrated in Fig. 8 as typical of the kind of results obtained in float experiments.

The next set of experiments, off Cape Verde (1966) at $12^{\circ}N$, $27^{\circ}W$, also were quite successful (Pochapsky, 1968) and involved two different clusters at depths of 3700 m and 4500 m. Temperature gradient instrumentation was added to some floats and this used two thermistors spaced 6 m apart vertically and connected in opposing arms of an electrical bridge. Vertical profiles of the temperatures and temperature gradients as a function of depth were measured at a free descending float. The sinking velocity itself of such a slowly descending float was investigated in detail as was the velocity of separation between two floats sinking at the same time but at differing depths at a given time. The latter measurements suggested the importance of determining vertical profiles of the horizontal current at vertical resolutions of 100 m or less. It was becoming clear that the vertical structure of horizontal shear was an important parameter whose knowledge might cast light on the relative importance of turbulence versus internal waves. No internal wave dispersion relations could be deduced for the noisy flow fields observed in any of the float experiments and the current shears, large in terms of the mean flow, suggested that a large vertical wavenumber was appropriate to the internal waves present,--if such gradients were not in fact reserved for inertia currents. On the other hand, vertical displacements were too large to be attributable to turbulence alone.

It was believed that the float cluster experiments as performed so far had revealed about as much as they would unless more operational capabilities were built into the system. The details of small-scale changes of current with

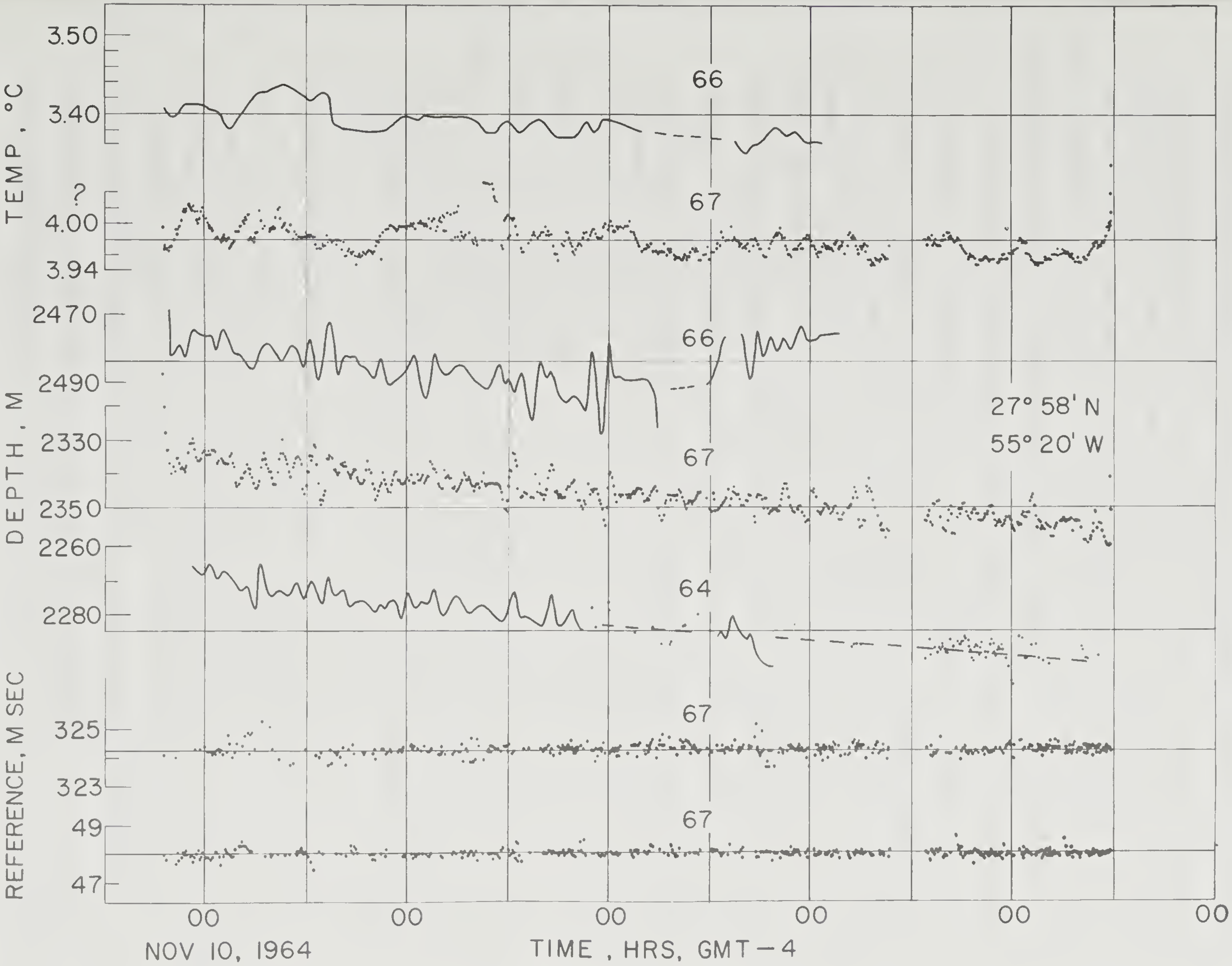


Fig. 8. Pressure, temperature and reference data

depth and of the absolute rather than the relative flow of a single hovering float, however, had been given a new importance and experimental procedures were biased more in that direction. For such studies, two new experimental features were added: 1) A means was evolved to attach to a float a bag of water displacing 11 times the volume of a float, as noted earlier. Water was loaded into the bag near the equilibrium depth in order to obtain a closer correspondence between the float and water movements at depth. 2) S floats were anchored on the sea floor as a listening array of transponders and the absolute position of a descending M float was to be determined from the separations to them. The latter measurements would yield the horizontal velocity as a function of depth. Experiments were performed (1967) in an interesting region at 10°N, 50°W where a deep AABW current flows northward. The possibilities that intense internal waves and instabilities accompany that current were among the topics to be investigated. The listening gains of the transponders apparently were set too low, however, because intercommunication was sporadic and satisfactory velocity data was not obtained. Nevertheless, interesting features of the movements of the "bagged" float were observed as it hovered for 5 days as were features of the vertical temperature structure and stability (Pochapsky, 1969).

At this time (1968) the Hudson Laboratories were terminated and the activities of the float program were continued on a lower budget at the Krumb School of Mines of the Columbia School of Engineering. The profiling scheme was tried again near the Gulf Stream off Cape Lookout, N. C. (1970) and a current profile was obtained despite adverse weather while operating from a small tug boat (Pochapsky and Malone, 1972). More extensive measurements were made

as part of the MODE experiments for the IDOE at two locations southwest of Bermuda during 1972-73. Operational difficulties were encountered at both these locations in that surface reflections sometimes upset the telemetering cycle and at the later location an alien transponder had a more serious effect on ping cycling. Nevertheless, both operations were highly successful. Repeated current and temperature profiles were obtained as a function of depth and in three profiling drops the floats were adjusted to descend to different hovering depths rather than to the sea floor. Absolute horizontal velocities during hovering were determined as a function of time and so results of the type sought in the earlier 10°N operation were now obtained in experiments off a small vessel which required only two racks of laboratory electronics equipment. Much of a procedural as well as of a scientific nature was learned in these later operations and results have been described in reports to be published (Pochapsky, 1975). Methods of converting measurements to velocities will be described in a subsequent section on profiling.

It is believed that a current profile, especially one that includes a profile on ascent obtained half an inertia day later, reveals more about the general vertical current structure than can be learned from an elaborate string of current meters averaged over a much longer observation time. Acoustic means seem to be the simplest for determining absolute currents, so including barotropic as well as baroclinic flow, and an adequate profiling system can be made simply of two inexpensive bottom transponders along with a simple interrogating transponder-type float which is used as a profiler. Depths can be determined from computations involving easily measured parameters which do not require detailed pressure measurements. There is no reason why one

bottom transponder cannot be used together with two profilers dropped at the same time but in orthogonal directions relative to the anchored transponder. A single profiler can be dropped from two such different positions at different times if simultaneity of measurements of the components of current is not required. The notion of using only disposable floats in profiling work is a reasonable one and the recovery of the profiler seems necessary only if that float contains a tape recorder which stores measurements of higher resolution than usually needed.

During the course of these experiments, efforts were made to develop shipboard processing equipment which would allow better monitoring of the experiments and produce digital data that could be analysed easily on board ship or on land. At the time punched tape was commercially better developed than magnetic tape and so incoming data was digitized, punched and displayed in graphical and decimal forms. Provision was made to edit tapes and to add interpolated data. Such processing equipment was bulky and required skilled engineering help on board ship to keep it operating properly at this early stage of development. Breakdowns could be expected and this meant that data had to be handled in somewhat primitive fashion. Some records were obtained on analogue tape recorders which stored hydrophone signals as they were received but those records were taken only sporadically and attention was too often diverted to take care of the more immediate requirement of the display of data as it was received so as to keep abreast of the progress of an experiment under way. Eventually the total of electronic equipment grew so as to occupy a half-dozen relay racks and the folly of this trend was shown when experiments had to be performed on smaller vessels. Furthermore, commercial computer software was developing to become more and

more adaptable to the kind of data processing involved in our experimental work and so our own engineering effort in this direction was considered unnecessary. Consequently, the amount of laboratory equipment taken on board was stripped to two basic racks of electronics gear and this still was sufficient to allow for float direction finding, aural listening, telemetering, analogue recording, multiplexing and decimal printout as well as for the storage of some auxiliary test equipment. The decimal printout was not always free of noise but the analogue tapes proved to be quite reliable and at times when the decimal recording on the ship was poor the corresponding analogue tapes provided data which could be analysed successfully on land by means of the correlator technique developed for these experiments. Even when listening was good it was found that the land-based reduction had an edge in quality over that obtained on the ship. It was concluded that the analogue recordings obtained at sea on a typical ($500) tape deck are so good that, if need be, a single rack of electronics can serve in the future to obtain all the float and navigational data required. These results emphasize the merit of instrumenting to obtain tape recorded data directly in M floats where the internal clock pulse will supply a reference signal which eliminates problems of multiplexing on playback.

INSTRUMENTATION AND ACCURACY

An M float by itself transmits acoustic doublets which measure the temperature and pressure alternately. Transmissions are repeated at a rate set on the M clock to be of the order of every 10 sec. Every few minutes a pressure or temperature doublet is replaced by a calibration reference doublet which measures, again alternately, the stability of

the lower and higher ends of the measuring scale and so which measures any _in situ_ circuit drifts.

The pressure gage is either of the variable reluctance or strain gage type while the temperature sensor is a single crystal silicon carbide thermistor (The Carborundum Co.) mounted in a 0.1-in D thin-walled stainless steel tube. Such sensors are included as arms of separate electrical bridges excited at a frequency of 1 kHz. The unbalanced outputs are amplified and rectified to produce a dc voltage which is almost linearly related to the change in the variable being measured. This voltage in turn produces a second tripping pulse when a voltage triggered by the first pulse to increase linearly in time attains an equal value. For convenience, the doublet trip occurs at 50 ms when the bridge is balanced. Full-scale unbalance of the bridge occurs at the value 550 ms. The two sensor bridges are connected alternately to the amplifier. Mechanical relays were used to accomplish that switching in early circuitry. FET switches now replace them. A third bridge has fixed resistors in each arm and these are adjusted to produce a constant value near 400 ms,--a value referred to as the upper calibration or reference. That bridge is connected to the amplifier so as to produce a single doublet every 4 min. A fourth doublet appears between these and this represents a shorted input or lower calibration signal to the amplifier. The shorted input reveals any zero drift in the dc amplifier while a variation in the 400 ms doublet time shows any change in gain.

Reactive as well as resistive balance of the bridge is required. Reactive elements in a nominally resistive bridge cause the unbalanced voltage to be not proportional to slight changes of resistance near the null point. This inconvenience is avoided by placing the sensor zero at a

point of slight bridge unbalance, say at 60 ms.

Thermistors presented few problems. Each is in a slender tube which slides a little loosely into a more substantial pressure-resistant housing which projects from the sphere. The time constant of the thermistor in the resulting protuberance is approximately 5 sec. The time constant of the sphere itself to changes of water temperature is almost the same during a slow descent. Among the difficulties were: 1) fragile thermistor leads which broke easily when handled, 2) insufficient seal against the entry of moisture at the lead end of the tube and 3) obtaining a low enough bridge current to assure no "hot-wire anemometer" effect in the velocity variations attending vertical profiling. In order to achieve a high sensitivity in deep work, the total scale range is reduced to 5°C. A surprisingly linear relationship exists between temperature and doublet time in that range. Calibration is done relative to a quartz thermometer which is adjusted at the ice point.

The variable-reluctance-type pressure gages have high outputs but they also have a number of disadvantages. Although pressure calibrations in the laboratory remained constant to within a few 0.1% over a period of months and remained accurate after mild mechanical jostling and rapping, something usually happened on the way to the ship because calibration shifts approached 1% on receipt. No reason for the shifts was found although many possibilities including changes in the environmental magnetic field were investigated. Among the other disadvantages were 1) a hysteresis of a few 0.1%, 2) large weight, 3) an eventual hysteretic weakening of the O-ring seals which resulted in water leakage at high pressures and 4) a sensitivity to thermal gradients across the gage. A gage was designed and built at the Hudson Laboratories to reduce the seriousness of those

flaws but it still did not have the stability desired. The answer seemed to come in strain-gage-type transducers. Although of lower output, this type performed very well in early operations. In later work, however, despite repeated checks on stability they started to drift seriously only during the experiments themselves. It is possible that our batch contained unknown defects incurred during manufacture although a defective gage was disassembled and found to be beautifully designed and built. Gages of this type, nevertheless, are probably the ones to use in future measurements.

In deep work, pressure fluctuations are smaller than are present in shallow water while the gage sensitivity must be lower in order to accomodate the large hydrostatic pressures. One method of increasing the sensitivity is to limit the range of pressure measurement and this was done by balancing the bridge when the pressure was at a value of 80% of the maximum pressure, P. Actually 40% of the total pressure can be measured because the range 0.8P-0.6P unbalances the bridge to the same alternating voltages as the range 0.8P-1.0P. A similar double scale can be utilized when measuring temperatures.

Pressure calibration was done using a large Bourdon-type standard in the laboratory and on the ship during the course of experiments. Temperature calibrations require somewhat more skill and so shipboard determinations were usually restricted to the ice point and possibly one temperature in the upper range. The repeatability of these calibrations as well as the stability of the upper and lower reference signals were monitors of the reliability of the sensor circuits. A time sequence of pressure, temperature and reference calibration signals obtained at sea is shown in Fig. 8. Most data represent averages for doublets

received over a period of a minute or so but calibration points are for single readings.

1. Internal clocking.

Internal clocks were designed to have minimal flutter or fluctuations from "tick to tick" and to have low steady drifts associated with temperature changes or aging. Flutter was of the order of 0.01 ms while the drifts in clocked intervals measured in seconds amounted to a ms or so over a temperature range of $20^{\circ}C$ or over a day of operation.

Sometimes the M float did not control the S float. Instead, both locked in an oscillatory mode in which they excited one another alternately or, at times, through the intermediacy of surface or bottom reflections. Non-multiplexed transmissions of this type often yielded good data provided that the M-float repetition rate was known accurately. A stable basic repetition or clocked rate is considered to be important and that period is measured to a fraction of a ms during the course of an experiment.

Other internal delays are 3 ms in the listening amplifier and 747 ms in the S float trigger delay circuit. Less accurately timed delays are present in rejection circuits which prevent exciting an M float oftener than every 40 ms and an S float oftener than every 3.5 sec.

2. Doppler effects.

Ship motions during listening in moderate seas can at times go through rapid velocity changes of 100 cm sec^{-1} in the vertical or horizontal directions. When such a velocity is present during the reception of a deep pressure 500 ms pulse doublet the hydrophone is displaced 50 cm and the

reception time of the second pulse changes by 0.5/1500 sec, or 1/3 ms. Deep temperature doublets are spaced closer, say 150 ms, and so would encounter a Doppler shift near 0.1 ms. In much past work, pressure and temperature readings were averaged over 1 min periods and for the typical 7 sec repetition rate that procedure reduced scatter by a factor of 2. All in all, it is expected that the usual Doppler scatter was less than 0.1 ms rms. The uncertainty of pulse resolution also contributes but a total system scatter of not much more than 0.1 ms is expected for past operations. This was confirmed when listening to bottomed floats.

Doppler produced errors are more important when separations are to be determined. In most past work with float pairs the separations remained below 3 km. The separation time was less than 4.75 sec and a hydrophone at a speed of 2 knots, or 100 cm sec^{-1}, would be displaced 4.75 m in that time so as to incur a timing error of 3.15 ms. This is equivalent to an error of 2.38 m in a measurement of the separation. If this change takes place between two consecutive clock pulses spaced 10 sec apart, then an erroneous velocity of 238/10 = 23.8 cm sec^{-1} is introduced. A general expression for this error is $\Delta v t_s/2t_c$ where Δv is the abrupt velocity change between two separation measurements and t_s/t_c is the ratio of the separation doublet time to data-interval clocked time. If, on the other hand, the hydrophone velocity remains steady between consecutive readings no error occurs. These extemes show the necessity of taking the conditions of reception into consideration. The error can be reduced rapidly by increasing the number of data points over which the velocity is obtained or by decreasing the resolution of the velocity as a function of time. For example, if 6 consecutive readings are averaged per minute and velocities are obtained over 1 min time

changes instead of every 10 sec, then the velocity error becomes $6^{-1/2} x 6^{-1} x 23.8 = 1.6$ cm sec^{-1}, provided gaussian random changes take place among readings of an rms distance of 4.75 m. The spectrum analyses of separations performed in float cluster experiments (Pochapsky, 1972) were obtained mainly over data-interval times of 10 or 20 min.

Because the separation time, t_s, changes fractionally only a small amount between readings, the Doppler-introduced velocity error is proportional to the acceleration between the time steps used and not to the steady velocities. This acceleration is largest for the rocking and pitching motions of a ship which have periods, say, in the range from 5 to 15 sec and so which produce large accelerations in the data sampling times. It is sometimes convenient to anticipate the magnitude of Doppler errors in terms of the differences of the displacements a hydrophone undergoes during consecutive separation readings.

In any except extremely smooth waters, it is likely that the velocity fluctuations determined over 10 sec intervals represent mainly Doppler noise. On the basis of this assumption, the background remaining after passage of the data through filters to reduce contamination, and resolution, can be estimated. If that noise spectrum of displacement as a function of frequency, f, is assumed to be white, the corresponding velocity spectrum should vary as f^{-2}. Such noise contributes relatively little to the variance of the velocity as the frequency is reduced and Doppler shifts are expected to contribute little at frequencies below the local water stability frequencies. They also have little effect on the accuracy of the separation measurement itself because they contribute only a distance equal to half the hydrophone displacement during the time interval of a separation doublet.

This discussion has shown the importance of obtaining separation data at non-accelerating hydrophones when high resolution data as a function of time or distance are required. The ideal method is to record such data at the M float itself and such a procedure presents few instrumental difficulties although it makes it necessary to recover such a float. Another procedure would be to build a mechanical filter against motion in the hydrophone line, such as a "yo-yo" mounting, which would reduce accelerations over the short time between consecutive readings. Such a line could be connected to a ship laying to or to a radio buoy.

TRANSPORT AND CURRENT PROFILING

Acoustic profiling utilizes the notion that a float moving up or down through the ocean column is displaced laterally only by horizontal currents and that the horizontal displacements of the float trajectory are determined by the horizontal current structure as a function of depth. Otherwise expressed, if the absolute trajectory of a profiling float is known together with the vertical velocity of the float as a function of depth, then the horizontal velocity is determined as a function of depth.

The net horizontal displacement over a depth interval is determined by the average horizontal water transport in that interval. It should be noted that the acoustic scheme yields a net transport as the basic measurement. Currents are obtained by differentiating that measurement with respect to time.

Three bottom-anchored transponders are required to establish a profiling trajectory based entirely on separations and the geometry of the transponder array must be

known. Originally it was intended that a profiling float would be dropped repeatedly into such an array from different surface locations and the array geometry would be determined from the sets of separations between transponders and the various profilers when bottomed. Orientation of the array would be determined from the ship's courses taken when the transponders were layed. This direction could be verified by ranging repeatedly to the transponders from a ship moving slowly on a known course. Pressure readings at the profiler could be used to check depths determined from the trajectories. On the other hand, when such pressure readings are available and supplemented with occasional ranges from the ship to remove ambiguities of direction, they can be used instead of distances to a third transponder to establish the trajectory. A third transponder then provides redundant information when pressure readings as a function of depth are available.

During operations at sea it was found that the two transponder system was so much simpler to use than a three transponder system that the redundancy associated with the latter was considered acquired at too high a cost. Reliance instead was placed on pressure gages to establish vertical velocities. Installation of a two-transponder system involves only two rapid drops while the ship is on a known course and so the direction of the array is easily established. For convenience, that array was alined N-S or E-W. The distance between the two anchored transponders is determined easily by letting the ship drift across their line of separation while acoustically ranging to them. Minimum transponded times occur when the ship is almost over that line.

Now the determination of the velocity of descent as a function of depth becomes an important factor. It is

required to know this velocity with an accuracy of a fraction of a cm sec^{-1}, or less. A fictitious fluctuation of vertical velocity, however, may be introduced as a result of pressure gage errors. The importance of those errors can be appreciated by noting that a drift of 0.1% of full scale, 6000 m, over a period of 10 min introduces and error of 1 cm sec^{-1}. The vertical distance covered in that time at a descent speed of 35 cm sec^{-1} is 210 m. A uniform change of the profiling velocity is not expected because internal waves may contribute variations amounting to a bit less than 1 cm sec^{-1} in waters below the main thermocline. When the effects of both rapid exterior temperature changes and mechanical factors on the pressure gage as well as on the circuitry are taken into consideration it is questionable whether measurements of velocity variations of this resolution are reliable enough in routine measurements to differentiate between internal waves and gage measuring errors.

A decision as to the method for measuring the profiling vertical velocity was made on the basis of some measurements made earlier near Cape Verde (Pochapsky, 1968). At that location two clusters were dropped at different times to two different hovering depths and the velocities of descent were determined from the pressure changes over 10 min intervals. The results are illustrated in Fig. 9. Even under these conditions of frequent pressure readings there was considerable scatter in the velocities obtained. The vertical velocities of three floats in a cluster showed a similar oscillation of 1 cm sec^{-1} over a vertical wavelength of almost a km in the shallow drop but variations were less than 1/2 cm sec^{-1} in a subsequent deeper drop. The gage of float 40 in the later drop was noisy and the effects of this on the velocity determinations were serious. It is

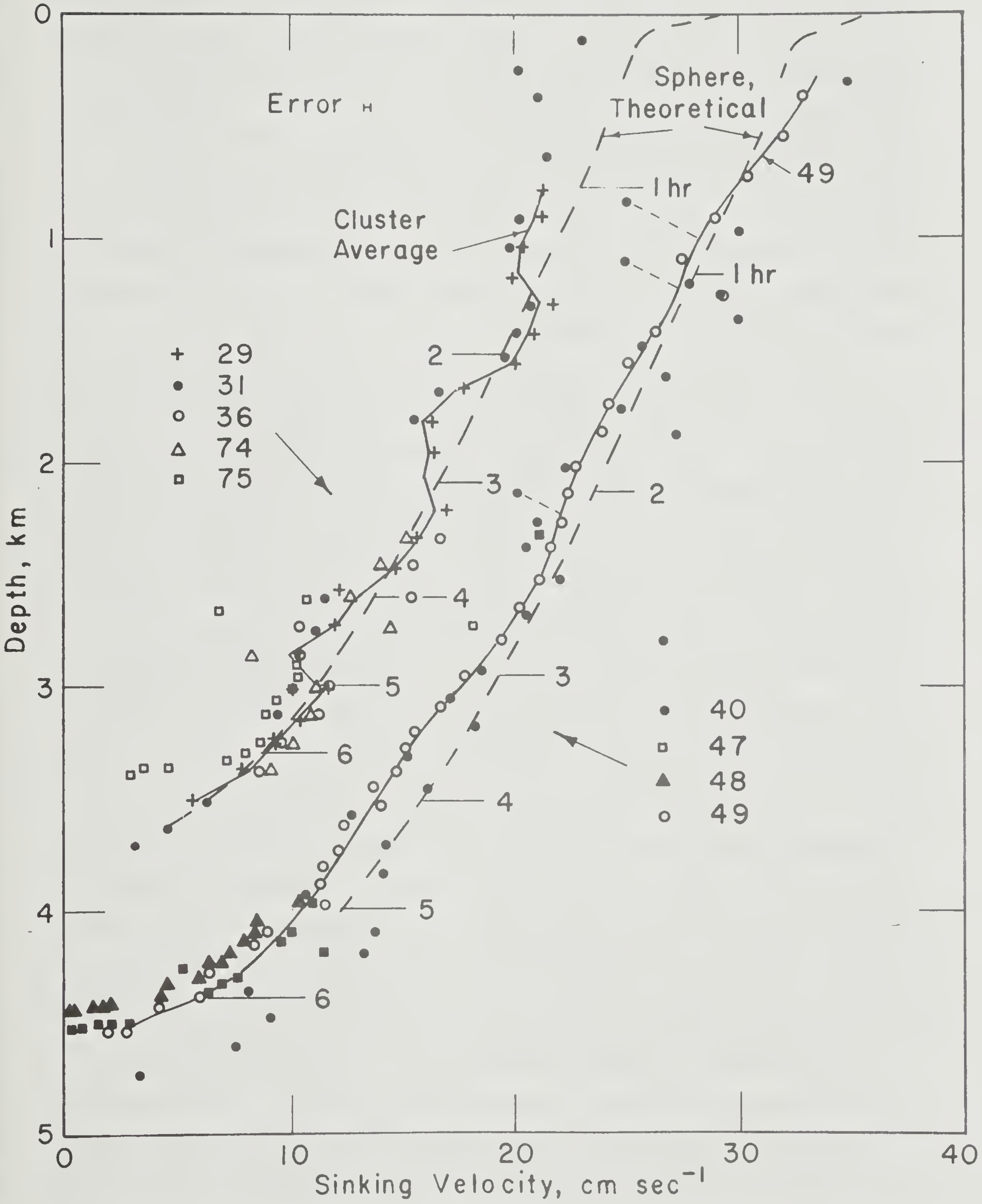


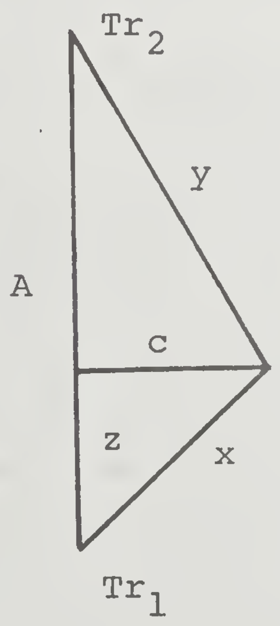
Fig. 9. Vertical velocities of sinking floats

probable that the common variations observed in either drop were produced by internal waves having almost a km vertical wavelength; at an assumed period of 10^4 sec the vertical displacement of such a wave having a 1 cm sec^{-1} peak velocity would have the reasonable amplitude of 16 m. The dashed lines on Fig. 9 represent theoretical velocities expected for a sphere sinking with the drag coefficient of 0.5 and subjected to a downward force determined by the difference in mean density of the float and the surrounding water as a function of depth.

The sinking velocities of floats during later profiling experiments were also determined on the basis of drag. Now, however, the drag coefficient instead of being set at 0.5 was established by the requirement that the calculated time of descent was identical to that observed. Suitable values of that coefficient were found to be near 0.7 for floats as used in the 1972 profiling work and 0.8 in the 1973 work. The external structure surrounding the float sphere is responsible for values above 0.5. Discrepancies between the velocities calculated on the basis of drag and those determined from pressure changes usually were less than 1 cm sec^{-1}. When greater differences occurred, it was the gage output which was suspect. These comparisons led to the conclusion that the theoretical velocities were more reliable and that it would be better to contaminate horizontal current determinations by neglecting weak vertical internal wave velocities than by introducing instrument errors. As will be shown, the contamination of horizontal velocities by various sources of error is least when the profiling float is deep or when the velocity component is obtained along the line joining transponders. Contamination is largest in the main thermocline but the fractional error is reduced in these waters where the horizontal fluctuations

usually are large.

The computational scheme obtains the horizontal projection of the separation between the profiler and each transponder from values of the separation distance as determined by the transponding time and of the height of the float above the ocean floor. The average velocity of sound to a transponder used to transform time to distance was taken to be constant when the profiler was in approximately the top km of water and to change linearly with depth below that; such values differed from exact averages usually by less than 1 cm sec^{-1}. Horizontal distances were obtained from averages over 5 clocked time steps; these averages were spaced approximately 1 min apart in time. The horizontal distances to both transponders and the distance between the transponders determine a triangle and the dimensions of this allow determining the coordinates of the moving profiler to the north and east of one of the transponders. Changes in that position over definite time intervals establish the N-S and E-W components of current.



This procedure is expressed analytically as follows: Let s_1 and s_2 denote the radial distances of a profiler to the transponders Tr_1 and Tr_2 which are A apart, while the profiler is at a distance h above the sea floor. Then the horizontal projections x and y of s_1 and s_2, respectively, are determined by the relations:

$$x^2 = s_1^{\,2} - h^2$$

$$y^2 = s_2^{\,2} - h^2.$$

When the transponders are alined from south to north, the horizontal position of the profiler relative to the southern transponder is

$$z = [\ A^2 - y^2 + x^2\ ](2A)^{-1} \qquad \text{north}$$

$$c = [\ x^2 - z^2\ ]^{1/2} \qquad \text{east}$$

The corresponding velocities are, where dots denote time derivatives,

$$\dot{z} = (s_1\dot{s}_1 - s_2\dot{s}_2)\ A^{-1}$$

$$\dot{c} = s_1\dot{s}_1 c^{-1} - h\dot{h}c^{-1} + z(s_2\dot{s}_2 - s_1\dot{s}_1)(Ac)^{-1}$$

Errors in the N-S velocity or along the line of transponders depend primarily on the accuracy of determinations of the separation velocities alone and these are reduced as the drop is made closer to the transponder line. They have no explicit dependence on depth but may depend on depth insofar as the separation velocities include vertical velocities. The cancellation of the velocity of descent in the expression for $\dot{z}$, however, is easily shown. Thus, the component of $\dot{h}$ in the direction of a transponder is $\dot{h}h/s$ and so $\dot{z}$ can be written

$$\dot{z} = (s_1 s_1^{-1}\dot{h}h - s_2 s_2^{-1}\dot{h}h)\ A^{-1} = 0$$

On the other hand, errors are not recessive for the E-W currents. Now the expression for the velocity is as given above for $\dot{c}$. The last term has the vanishing properties discussed for $\dot{z}$ but the first two terms are not as obliging. If there were no horizontal current the first two terms would cancel provided they were known exactly. The second term, however, may contain real fluctuations which are ignored in the smoothed relationship adopted for the vertical velocity and so those errors as well as the

other errors typically associated with the measurement of $\dot{s}$ appear and unfortunately are magnified by the term c^{-1}. Obviously no E-W velocities are obtainable when profiling is done close to the transponder line where c approaches the value zero. All errors are magnified by a factor of approximately 2 when c has a value comparable with the depth of the water.

As an example of the magnitude of these errors, consider a situation where the ocean is 5.5 km deep and where c = 3 km and A = 7 km. Let the drop be made equidistant from both transponders at a velocity of descent of 30 cm sec^{-1} in an E-W current of 10 cm sec^{-1}. When an error of 1 cm sec^{-1} is made in $\dot{s}_1$ near the surface then the error of $\dot{c}$ is 2.4 cm sec^{-1} while a similar error in the velocity of descent produces an error of 1.8 cm sec^{-1} in $\dot{c}$. At mid-depths the errors would be 1.8 and 0.9 cm sec^{-1}, respectively. Error magnification increases as c is reduced at a rate almost inversely proportional to c. Thus, if c were 1.5 km instead of 3 km, the magnitudes of the errors would be 5.5 and 3.7 cm sec^{-1} at the surface for errors of 1 cm sec^{-1} in $\dot{s}_1$ or $\dot{h}$.

The various considerations of this section are demonstrated by some of the results illustrated in Fig. 10. This profiling drop was from a point at the surface near z = 3 km and c = 2 km for transponders spaced 6.9 km apart in 5500 m of water. The horizontal trajectories obtained during the descent and ascent, normalized to a 35 cm sec^{-1} profiling rate, are illustrated in the right of this figure. Data points are 1 min apart; data gaps occur during poor listening conditions or when the ship is in transit to a better listening position. The N-S and E-W current profiles are presented to the left. The jagged curves are for 1-min velocity data and the large wavenumber hash on these is

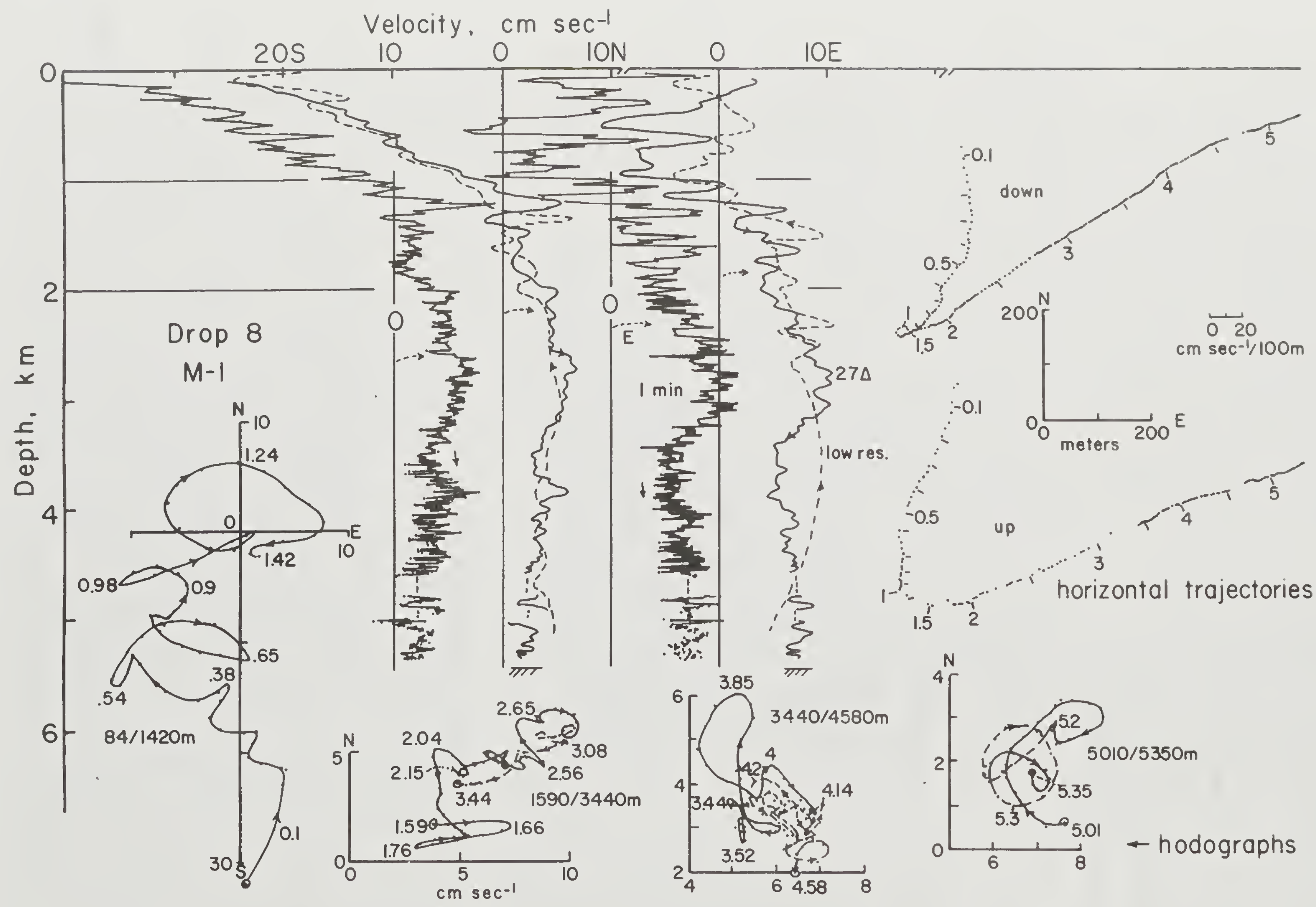


Fig. 10. Horizontal displacements and currents during profiling

attributed to rocking motions of the ship. After filtering, the solid curves to the right of these are obtained; superimposed on these are dashed curves for the currents on ascent. As expected, the noise filters out rapidly. Note that the E-W noise is not greatly more than the N-S noise despite the small value of c. Fig. 10 also includes hodographs of the horizontal current which illustrate vector velocities as a function of depth after filtering.

ELECTRONIC INSTRUMENTATION

1. Float electronics.

The different electronic functions performed in a float are illustrated schematically in Fig. 11. The acoustic pinger is powered at frequencies of 10.5, 12 or 13.5 kHz supplied in pulsed bursts lasting from 5 to 10 ms. The accuracy of the data telemetered depends on the tolerances of the times within which the keying of those bursts takes place. A keyer generates a timing gate every 5 to 10 sec which turns the oscillator on for a time of 5 to 10 ms. Tripping pulses from the listening amplifier caused by signals at the hydrophone also cause the generation of such square pulses in the keyer. In addition, the keyer clock trips a ramp generator which then generates a voltage that increases linearly with time for a little over 1/2 sec. When this increasing voltage has a value that is equal to that from the sensor bridge, a sharp spike is produced which enters the keyer to generate another pulse gate. The time between this pulse and the clock pulse is proportional to the unbalanced voltage at the sensor bridge. In transponders, the sensing circuit is replaced by a simple coding circuit which supplies a second pulse at a preset delay time after receiving the clocking pulse.

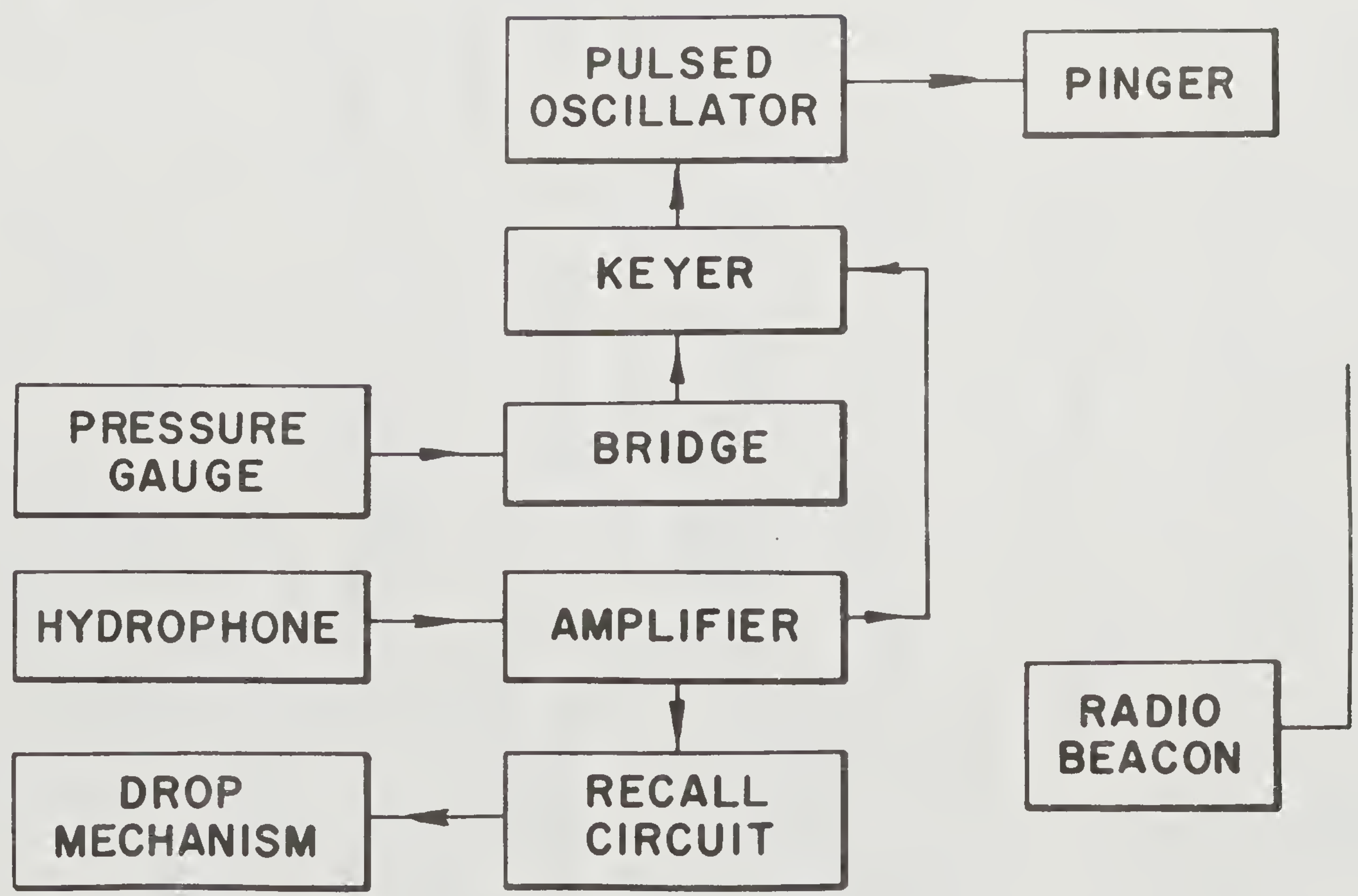


Fig. 11. Schematic of float instrumentation

Tripping pulses from the listening amplifier may also be sent into a recall circuit. When such pulses appear in a specific coded sequence they close a switch which actuates the surfacing weight-dropper motor. As noted earlier, a suitably restrictive code was not found in the limited tests performed and so recall circuitry has been omitted as a nuisance in more recent work.

The radio beacon has been described earlier and reference is again made to the circuit of Fig. 7.

Another version of a schematic diagram for the electronic functions is shown in Fig. 12 which illustrates how operations are allocated among individual printed circuit boards. Circuits specific to particular boards are illustrated in Figs. 13, 14 and 15. Values of circuit elements are shown only occasionally in order to illustrate magnitudes.

Exclusive of the power oscillator, all the circuits of a fully instrumented float take a current of 13 ma at the terminals of a 32-v battery and 12 ma at a 39-v source. The 32 v is supplied by Mallory RM-1450 mercury cells to which 7 v of RM-1438 cells are added in order to obtain the 39-v supply. The resulting battery weight is 3 lb 11 oz. Mallory RM-1438 cells make up the 45-v pinger power supply in a battery weighing 3 lb 7 oz. Such batteries have operated for over 5 days at the duty cycles used in our experiments.

Pinger drive

All floats have much the same circuitry from the keyer through the power oscillator as is detailed in Fig. 13 which applies specifically to transponders. The power oscillator excites the pinger at a voltage of approximately

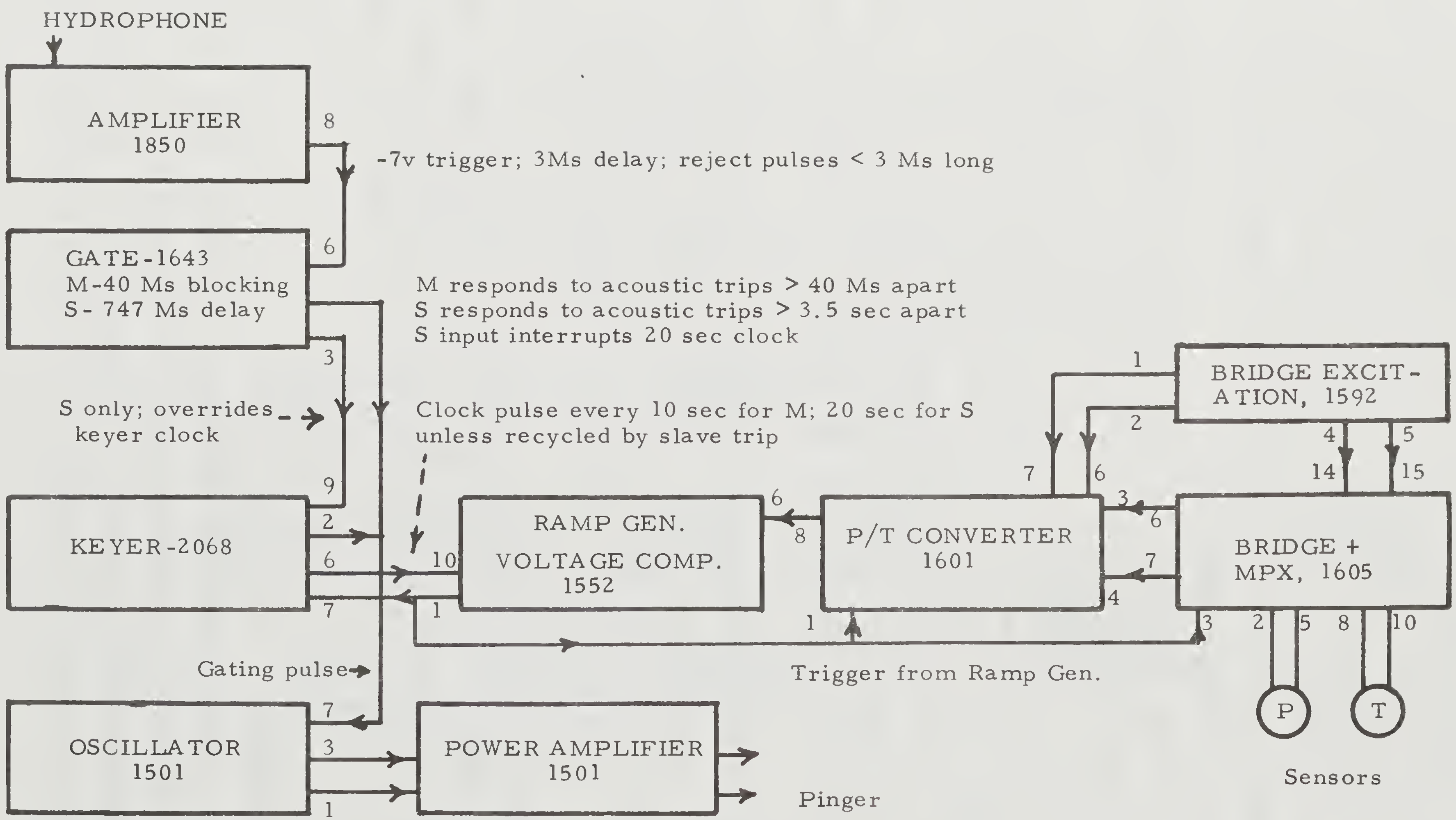


Fig. 12. Schematic of float printed circuits

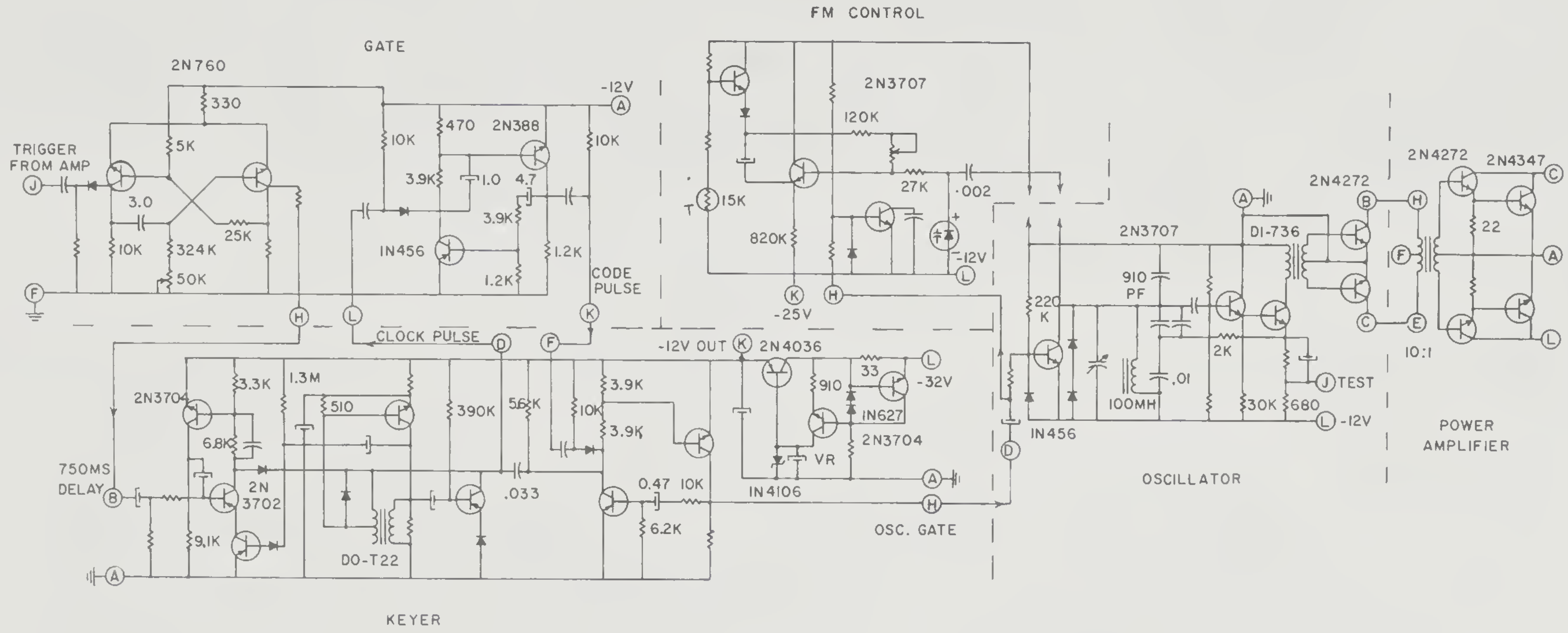


Fig. 13. Transponder electronics circuits

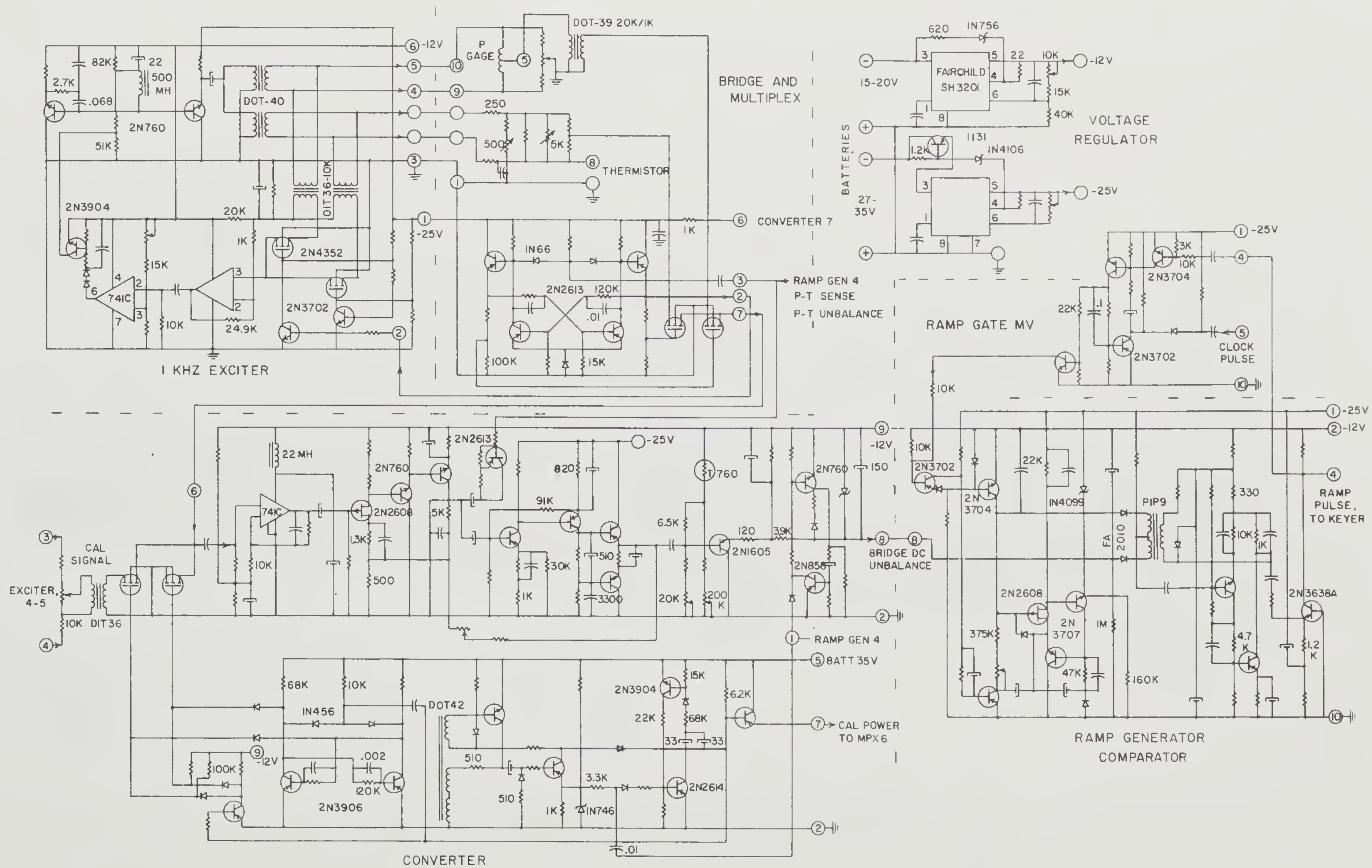


Fig. 14. Telemetering circuits

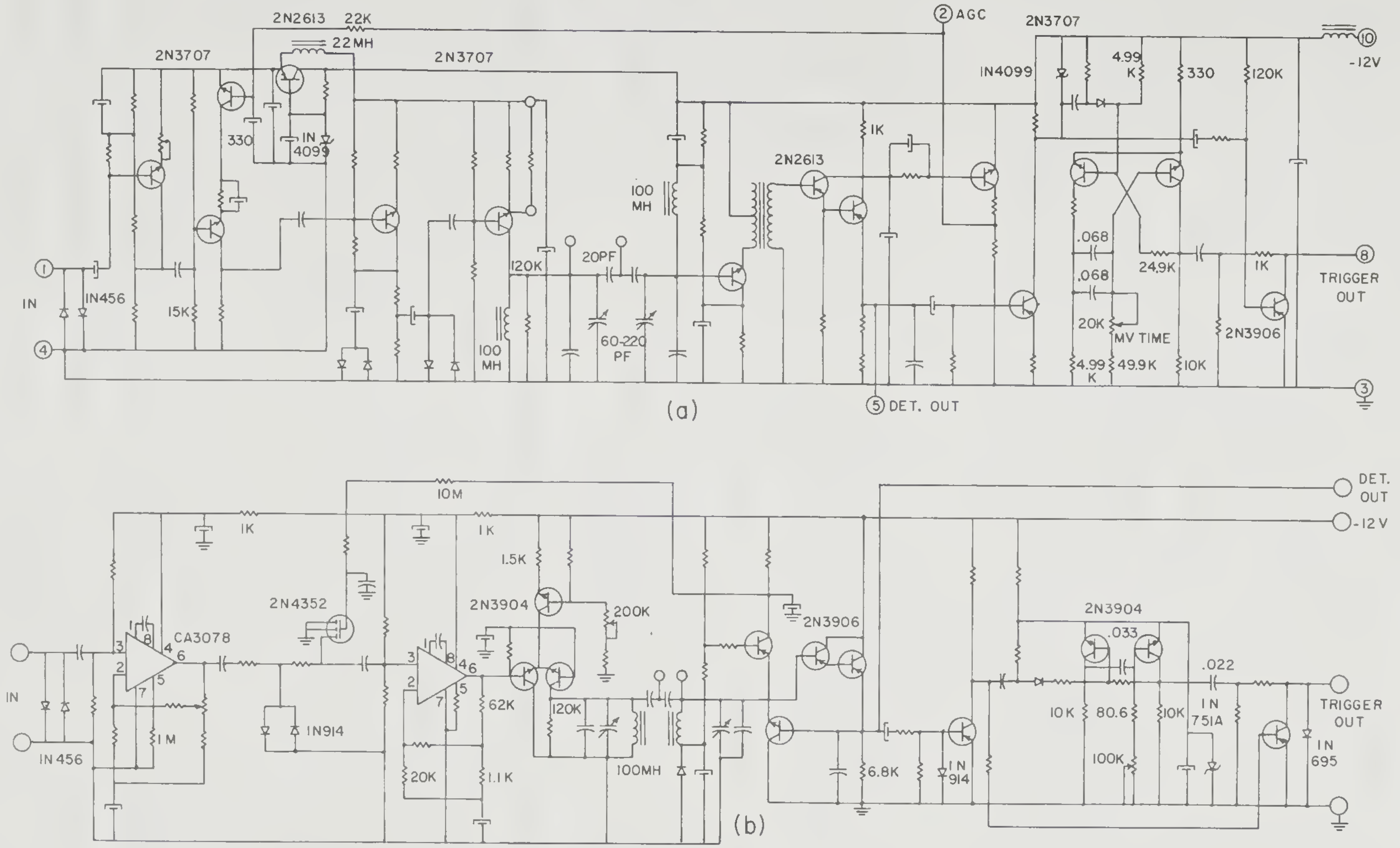


Fig. 15. Amplifiers

700 v rms after the transistor output is stepped up through a transformer not shown. For a transformer input of 63 v, center tapped, the output can be selected in steps over the range 680 v to 1000 v at no load. The transformer weighs 14.5 oz and has a core cross section of 1/2 x 5/8 in. A variable inductor, or loading coil, across the pinger is adjusted to obtain maximum voltage when the pinger is in water. That inductor compensates for the large capacitive loading presented by a ceramic-type transducer. The 45-v mercury battery power source is kept connected across a 4000 mf capacitor.

In a transponder, the pinger also serves as a hydrophone. This is made possible by connecting the pinger and loading coil combination to the power transformer through a pair of parallel opposing diodes, 1N4004, so that output circuit electrical noises are not heard at the input to the amplifier. The pinger also is connected to a preamplifier through a 47k resistor and opposing diodes limit the input voltage to that preamplifier.

Oscillators have included the FM circuit shown in Fig. 13 only on M floats so far. These use a varicap to shift the mean pulsed frequency through a range of $\pm$ 1/2 kHz during the time of a single ping so as to produce an FM chirp. A signal of this type can be detected with a higher time resolution than can a ping of constant pulsed frequency.

Although the clock pulse in an M float always is controlled by its own circuitry, an S float is usually controlled by the received M-clock signals rather than by its own internal clock. This results because any incoming clock pulses which are repeated faster by 1 sec or more than the S-clock time will block the S clock and control the S repetition rate. An S-clock period is usually set near 20 sec

in contrast to 10 sec for the M clock. M-sensor or reflected pulses received up to 3 or 4 sec after the M-clock pulse is received at the S float are excluded from the S keyer by a blocking action retrigger time which is set by the 1.3 M resistor and series capacitor connected to the secondary of the transformer in the keyer, Fig. 13. The repetition time of the keyer or the clock pulse time is set by varying the 390 k resistor leading to the base of a transistor connected to the output of that transformer as well. This resistance is increased by a variable resistor not drawn in the circuit shown. An associated capacitance of approximately 30 mf is used.

Coding or sensor tripping pulses enter the keyer at terminal F, Fig. 13, while signals from the listening amplifier enter at terminal B.

<u>Sensor circuits</u>

Circuits used to obtain stable sensor measurements are illustrated in Fig. 14.

The ramp generator and voltage comparator circuits are shown at the right of Fig. 14. There, the clocking pulse enters a gate through terminal 5. This input gate to the ramp generator is reset by the output sensor pulse to the keyer, terminal 4. That input trigger initiates a linear increase in voltage or ramp which appears at the upper terminal of the primary of transformer PIP9. The slope of the ramp is set by adjusting the variable resistor on a lead to that terminal. The dc unbalance from the sensor bridge is applied to the lower terminal of that primary. The net unbalanced voltage across the primary and the output of the secondary are used in a feedback circuit, at 2N3638A, to obtain a sensitive null detector which establishes the time when the unbalanced dc bridge output and the ramp voltage

are equal. When the sign changes at the zero crossing, a sensor keying pulse is generated which appears across terminal 4.

The dc voltage which measures the bridge unbalance is generated on the converter card whose circuitry is drawn in the lower left portion of Fig. 14. In order to obtain a voltage which is always reproducible for a given sensor unbalance a number of requirements must be satisfied. These include 1) circuit components whose properties do not change with time, temperature, accelerations or electrical current, 2) immunity to circuit transients or activity in these or other circuits in the float, 3) a constant bridge excitation voltage, 4) a constant gain of the dc amplifier which amplifies and converts the ac bridge unbalance into a dc voltage. Four quantities --pressure, temperature and two calibration signals--are sensed and the associated switching must not produce transients which persist from one reading to the next.

The ac voltages supplied by the bridge unbalance are introduced into the dc amplifier at terminal 6 which then leads to the operational amplifier 741C. Amplifier gain is set several stages later at the variable resistor shown in a line leading to the collector of a transistor. Rectification is accomplished at the 2N1605 transistor which incorporates a thermistor, T760, to achieve temperature stability. A 20 k resistor connected to the base of that transistor establishes the lowest voltage at the output and is set so as to obtain a 50 ms doublet at the low end of the scale of the variable being measured. Circuit gain from input to rectified output is approximately 250.

Specific input variables to the 741C amplifier are selected by the FETs drawn near the input terminal of the

converter board as well as by those on the bridge and multiplex board. Usually the former are connected to the latter which switch alternate pressure and temperature signals. Every few minutes, however, they switch to the upper calibration reference signal which is produced at the resistors across the terminals 3 and 4 of the converter or to the zero input voltage reference. Switching instructions to the input FETs are generated in the circuits associated with the transformer DO-T42 shown on the converter board.

Alternations between the pressure and temperature bridges are made at the FETs on the bridge and multiplex board which are shown with their associated multivibrator circuits.

All changes of signal type at the input of the dc amplifier are made by the second pulse of a doublet to that the bridge circuits can have at least 6 sec of time to become stabilized before their voltages are sampled.

The circuit for generating the constant 1 kHz voltage used to excite the bridges is illustrated in the upper left of Fig. 14 together with circuits for the bridges. Details of the bridge circuitry depend on the particular sensors used and so such circuits are drawn only sketchily. Recent floats use strain-gage-type pressure gages and SiC thermistors with a step-up transformer, 200 ohm to 500 k, in common. These pressure gages have internal bridges, 350 ohm per arm, with a full scale sensitivity of 3.9 mv per volt of excitation. Thermistors have a resistance of 4500 ohm at $0^{\circ}C$ and 3500 ohm at $10^{\circ}C$. Voltages driving the thermistor bridge are kept below 25 mv.

Amplifier

Two versions of the amplifier used in floats to convert

signals from the preamplifier near the hydrophone into triggers for the keyer are shown in Fig. 15. The upper circuit, a, has been developed over the years and is used for reliability; the lower circuit, b, is an attempt to modify this by using more recent solid state components. Unfortunately, the lower circuit, as is, has not passed laboratory tests because the integrated circuits are relatively noisy and tend to oscillate outside of a small range of gain. It is expected that newer operational amplifiers will not have these limitations and so the lower drawing is included as an indication of the direction that experience with floats at sea suggests modifications might be made. Some of the difficulties result from the requirement that circuits draw unconventionally low currents. The amplifiers used draw less than 3 ma.

The preamplifier, not illustrated, uses two transistors to realize a gain of approximately 10 as well as to obtain a lower source impedance from the hydrophone terminals located in the lower hemisphere of a float. It uses two 1N456 diodes as limiters at the input.

Further limiting is done at the input and at various stages of the main amplifier, as shown in Fig. 15a. Little filtering is done until the amplified signal is ready to be rectified. This arrangement was adopted in order to obtain an improved reaction to overloading by sea noises. Construction of the filter is shown in the drawing located between the two stages which feed the transformer to the detector 2N2613. Standard elements are used and any frequency desired within the pinger range can be obtained. An AGC is built into the detector circuit.

The rectified signal enters a multivibrator-controlled pulse generating circuit where the leading edge of the

signal, in effect, arms the trigger output. If the signal does not persist longer than 3 ms, no output trip takes place. If the time exceeds that, a trip occurs at a constant time delay established by the setting on the variable resistor in the MV circuit.

Float amplifiers have been set to trip in quiet seas for pinged pulses exceeding 18 μv at the input. The preamplifier gain was 6 and so tripping occurred for a 3 μv signal or approximately a 0.1 dyne cm^{-2} pressure at the hydrophone. For sea state 3, the rms ambient noise pressure is 0.03 dyne cm^{-2} over a 1 kHz bandwidth at a frequency of 10 kHz.

Amplifiers have a frequency response which is almost flat in the range $\pm$ 0.3 kHz of the center frequency, f_o, and then falls to have -6 db points at $f_o \pm 0.7$ kHz and a -20 db response at approximately $f_o \pm 1.5$ kHz.

Sea noise is far from white and so the AGC action is best studied by using taped sea noise at the input.

2. Rack equipment.

The shipboard electronics equipment serves to 1) give a continuous aural presentation of the course of acoustic telemetry, 2) amplify and filter signals received at the hydrophones, 3) obtain analogue tape recordings of the reception at a hydrophone together with a 10 kHz frequency time reference, 4) remove unwanted echoes and cycle the incoming data to follow the multiplex scheme established by the M-float clock, 5) measure pulse-time intervals and print these along with Greenwich clock time in decimal format, 6) perform additional signal processing and graphical display as well as record in digital form, 7) interrogate

floats beneath the surface and 8) store replacement and test equipment. All these functions except for item 6) can be accomplished by using the three basic racks shown schematically in Fig. 16. The functions of item 6) require two additional racks which are not illustrated here. The third rack, Fig. 16, is needed only when listening conditions are poor. If necessary, experiments can be done using only the first rack which makes it possible to track floats and obtain analogue records that can be analysed off-ship.

Most of the uses of equipment listed on rack 1 are evident. The amplifiers consist of a bank of 4 identical units and any of these can be switched into the listening system which heterodynes incoming signals into frequencies convenient for aural listening. Each amplifier has front panel controls which enable the selection of broad band reception or narrow bands 1 kHz wide at center frequencies of 10.5, 12 and 13.5 kHz. In addition there is a threshold control which sets the level at which incoming pings can generate outgoing trigger pulses which are sent on to the 3-channel multiplexer located on the second rack. Acoustic signals are recorded broad band as they come in and the 10 kHz reference signal accompanies them on the second channel of a tape run at 3 3/4 ips.

The difficult task of measuring intervals between acoustic pulses in proper time sequences where only specific intervals are to be measured is assigned to the 3-channel multiplexer. A coding pulse present in the pinged M-float clock output would simplify this process but complexity in the "on hand" shipboard equipment was preferred over adding to the functions of a float which is inaccessible during the course of an experiment. It is the task of the multiplexer to keep measurement cycling in phase with the M-float clock pulse and this is accomplished by setting the multi-

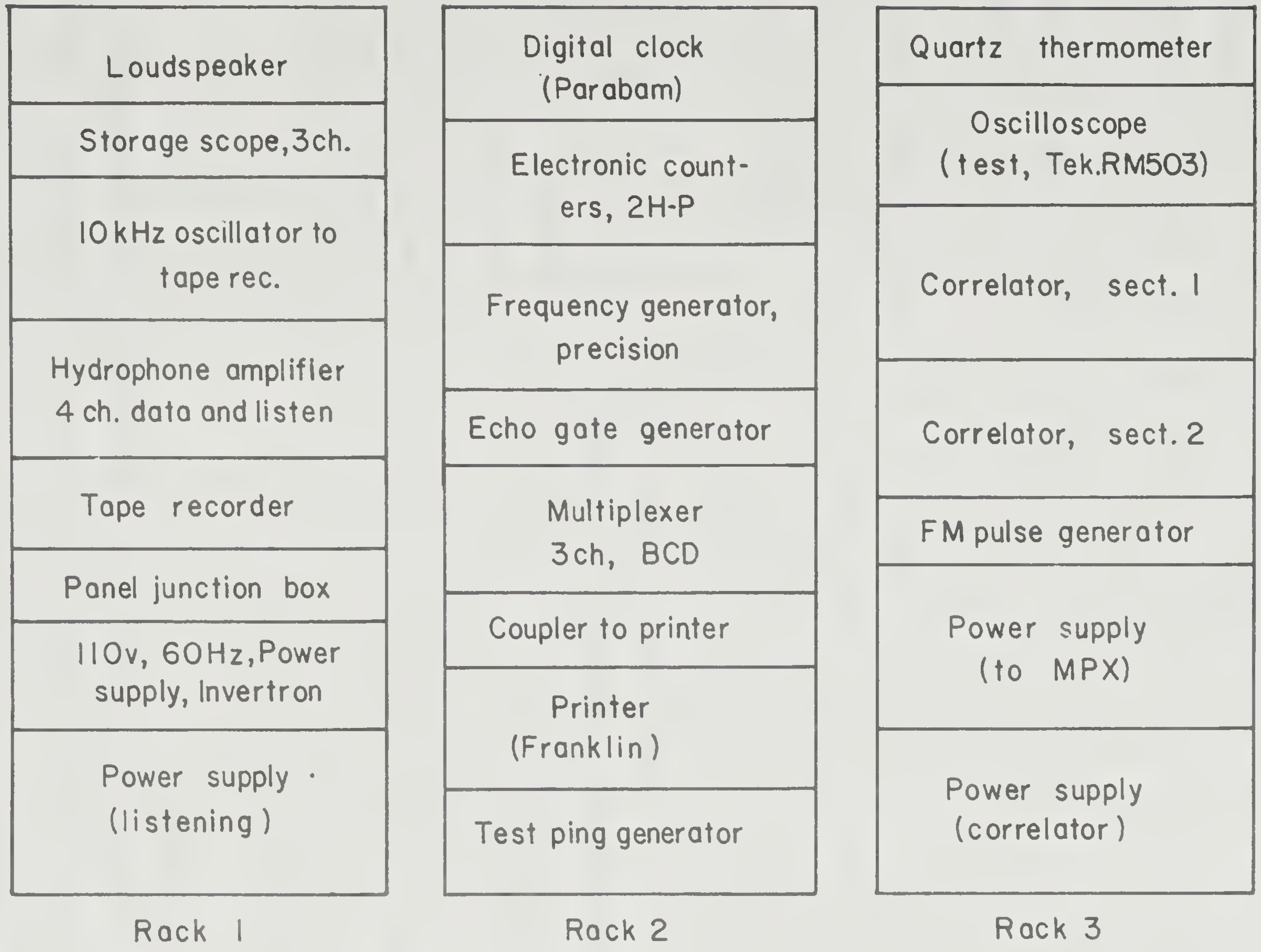


Fig. 16. Shipboard listening-recording equipment

plexer cycling time by means of a panel control to be a little faster than that of the M clock. Synchronization is obtained by pressing a panel switch at an appropriate time. The time between the M-clock and the M-sensor pulse is printed in decimal format to a count of 0.1 ms together with Greenwich time to 1 sec as soon as the second or sensor pulse stops the time counter. Each M-clock pulse also starts a second counter which is stopped by the first S-float response. That separation time is stored before it is printed until after the S-sensor pulse time has been printed. Decimal printout for a pair of floats is in sequences of triads of M-sensor, S-sensor and separation times. Variants of this scheme are built into circuits as needed. Thus, a series of transponder separation times can be received and printed together with their codes by catching times "on the fly" off a single counter.

No circuits for the multiplexer as used are illustrated here because they are considered superceded by new circuitry which takes advantage of recent developments in solid-state technology.

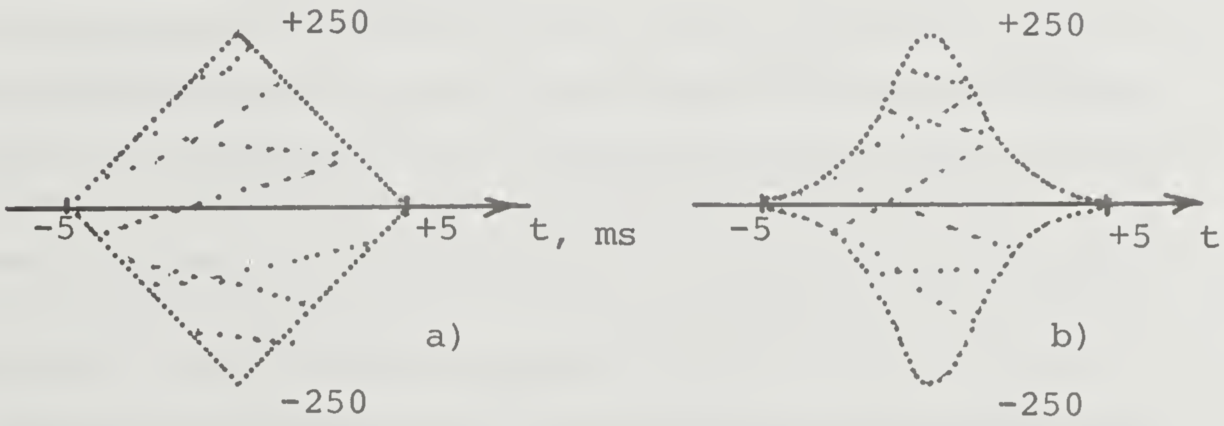
Sometimes troublesome repeated echoes are present. These can be removed by letting the clocking pulse trigger a gate which prevents passage of such an echo during a controllable time interval. That function is performed by the Echo Gate Generator in rack 2.

Correlator

The correlator used for matched filter reception is located in the third rack. Here too, advancing technology has made the voluminous current-consuming circuitry used in past work unsuitable for duplication but operational features of that correlator are such that a limited description

of it and of a more recent model is useful. This correlator has made it possible to obtain data under conditions where data would not be resolvable when using simpler filter and pulse-time processing techniques.

Correlation is done on the ping train after it is clipped and so is based on the positive and negative signs of the incoming wave pressure. When such a train is divided into 250 equal time divisions and the polarity at each division is instantaneously stored in 250 distinct bins, a digital sample strongly characteristic of the train is obtained. Any other incoming sound can be time divided in the same way—every 1/50 ms for a 5 ms ping at 10 kHz—and each of its 250 signs compared with those stored. When a train identical to the original is viewed and compared, there is a complete correspondence and if each match is assigned a value of unity and all are added the result will be a sum equal to 250. On the other hand, a wave completely out of phase produces a sum of -250. Noise is just as apt to agree or disagree in sign at any interval and so it contributes nothing to the sum. As a 5 ms long train enters and passes by, the sum at 1/50 ms intervals as a function of time appears somewhat as illustrated in sketch a) of the following figures:



A triangular envelope is obtained when a wave of constant frequency is pulsed but a bell-shaped one, b), occurs when the frequency changes proportionally to the time. The arrival time of either pulse is detected when the sum is at a peak and the resolution of that time in the presence of noise depends on how close to the peak the tripping threshold can be set. It is apparent from the figures that the arrival time of a frequency modulated pulse can be established more precisely than that of the constant frequency burst.

The theory of matched filter detection can be found elsewhere. We only state its empirical value here as shown by experiments at sea which show a reliability of reception time resolution of approximately 0.1 ms and a clear superiority over conventional techniques under adverse listening conditions.

Two methods of summing can be used. In both, a reference signal is permanently stored in one series of, say, 250 bins while signals received are continually passed through a second sequence of 250 bins in steps of 1/50 ms. In one method, however, the addition is done by wiring up the 250 bin comparison outputs in series and sampling the sum present at every increasing time interval of 1/50 ms. This is the scheme of the correlator used in our experiments at sea. In the second, the summation is done by electronically sampling every bin of the 250 in succession during a 1/50 ms step and obtaining a sum by integration rather than by direct addition. This second, or deltic, scheme requires much less wiring but switching must be done 250 times in every 1/50 ms step and so at least every 0.08 μs instead of every 20 μs. Circuit frequencies of 15 MHz are needed to accomplish this instead of the 50 kHz of the earlier version. Solid-state components capable of functioning at such high

frequencies were not available at the time the original correlator was built for float work and so the first or slower form of addition was necessary. Three channels of 250 storage registers are used—one is for the stored reference and the other two for independent incoming signals. The original solid state elements are bulky and 25 sizable printed circuit boards are required to perform the comparison and addition functions. In contrast, two channels of 250 bits each recently were built into a deltic correlator on a single printed circuit board of somewhat smaller dimensions than used in the earlier correlator. The newer model has operated satisfactorily in preliminary laboratory tests and looks promising for use at sea. The small size and low power requirements make it highly suitable for shipboard use. On the other hand, trouble shooting at those high frequencies can present practical problems. Furthermore, improvements in integrated circuitry may allow sufficient savings in space and power in a redesigned direct summing correlator and perhaps an additional flexibility in application. These comments are made to suggest that both schemes be reevaluated before deciding on which to use in the future. One consideration in such deliberations should be the possibility of incorporating correlators within float circuits themselves.

In addition to needing a storage register, correlators require circuits which digitize the incoming signal and supply the clock pulses necessary to step signals through those registers and which allow replacing a stored signal with a different one. A schematic diagram illustrating these functions is shown in Fig. 17. Further details of the clock and digitizing circuitry are shown in Fig. 18. A stable clock is essential in order that the frequency of the stored signal not appear to drift as a consequence

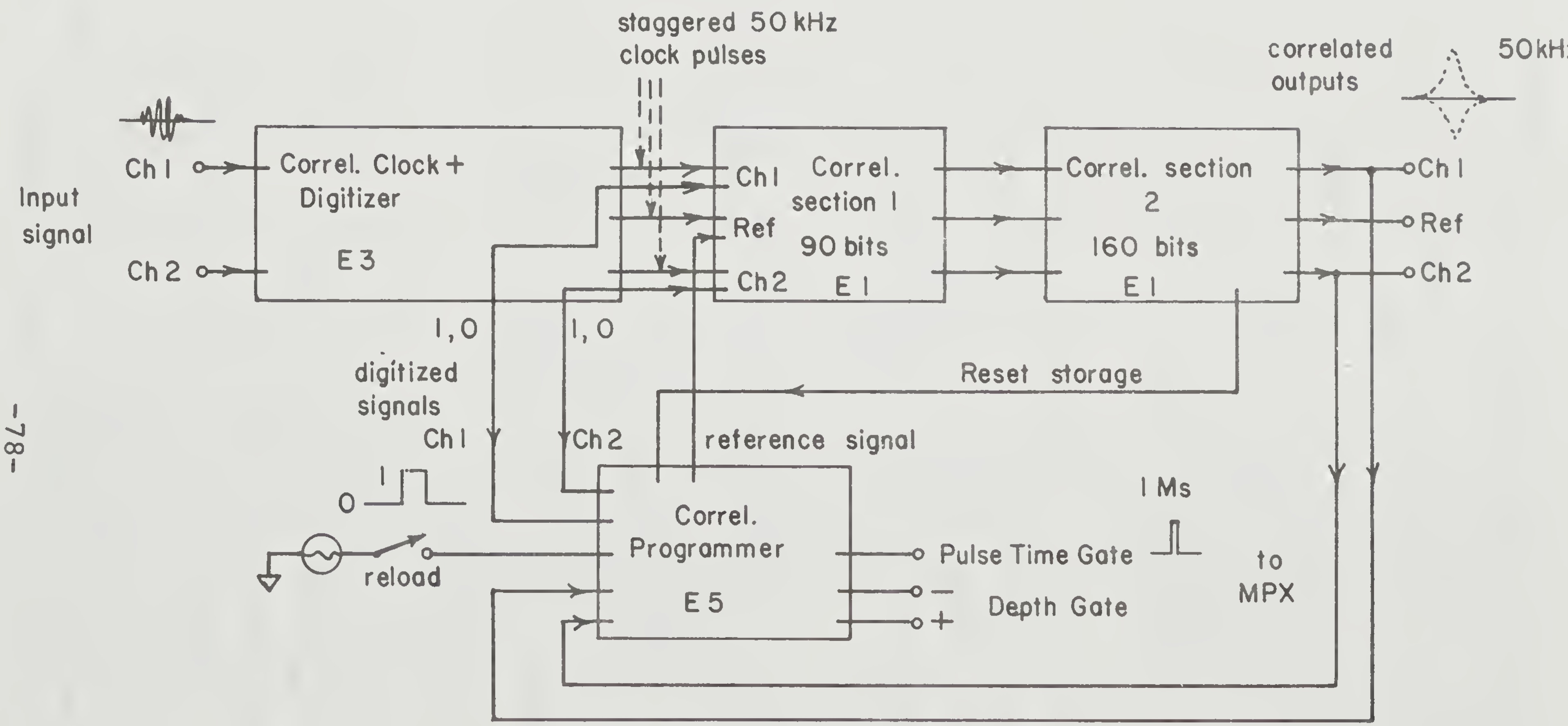


Fig. 17. Correlator schematic

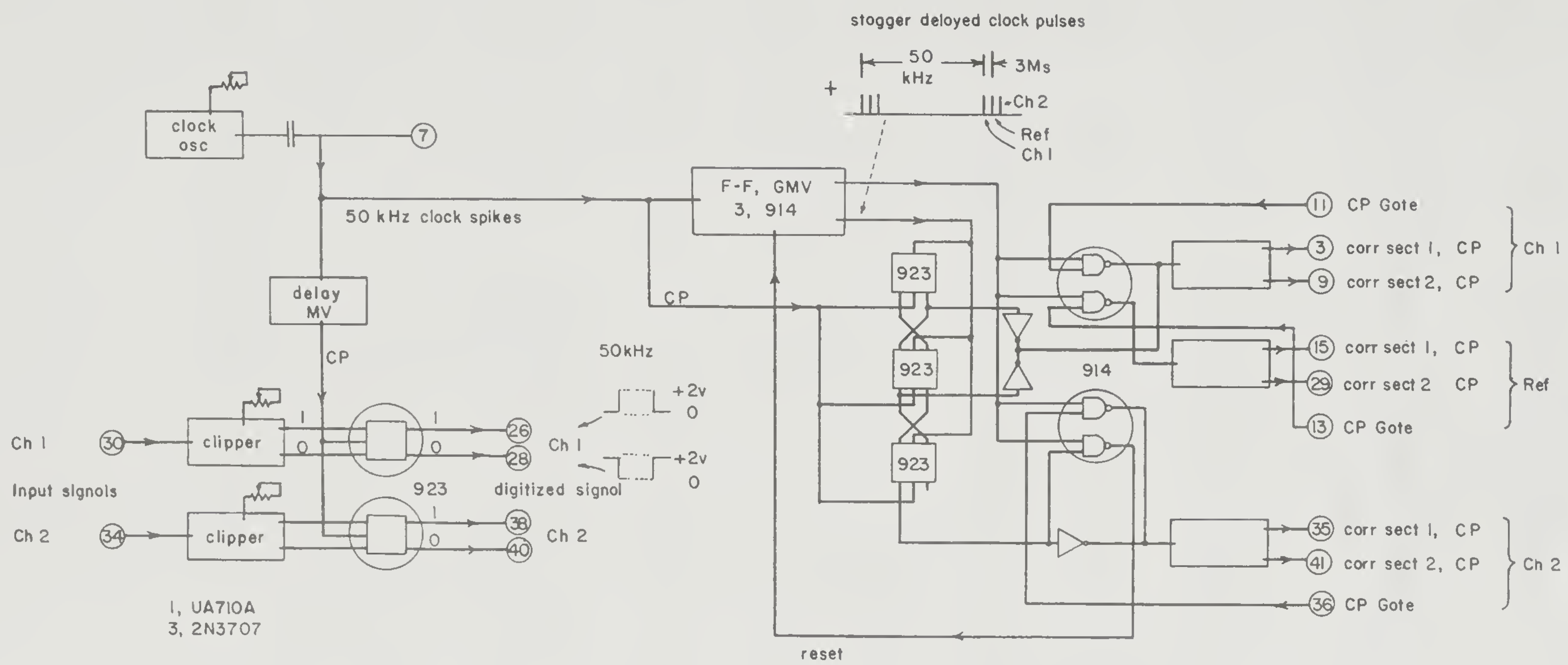


Fig. 18. Correlator clock and digitizer

of changes in the stepping time. The 50-kHz clock spikes also control the time intervals used for digitizing the input signals. In order to avoid transient interactions between the three registers, they are clocked at staggered times. The method used to introduce delays of 3 μs between triggers in the adjacent registers is illustrated in Fig. 18.

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Instrumented neutrally-buoyant floats were used in a series of experiments performed over a number of years starting at the Hudson Laboratories of Columbia University in 1957. This report reviews the scientific motivations for such experiments along with the continued instrument development required. The early work was the first to measure actual oscillatory vertical displacements of tens of meters such as might be associated with

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internal waves in deep water and also revealed intense vertical shears of the horizontal currents at all depths. Attempts to show that motions satisfied the dispersion relations for internal waves were frustrated by the noisy character of those motions. Such studies were done using clusters of intercommunicating floats hovering near the same depth. Important contributions to the kinetic energy by internal waves were found but the importance of intrinsically turbulent motions remains enigmatic. Inertia currents were shown to dominate almost everywhere. The role of those currents in energy transformations has yet to be established and detailed measurements of their changes with depth may be important in that regard. Measurements of the total current vector in profiles as a function of depth were performed and these showed the presence everywhere of large gradients such as were observed locally at clusters.

Most of the scientific aspects of this work have been reported in previous publications by the author but little has been presented on the type of instrumentation and on the methods of acquiring and processing data. One of the purposes of this review is to present essential details of those experimental aspects.

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